Experimental study on non-boussinesq plumes and compartment fires

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Experimental Study On Non-Boussinesq Plumes And Compartment Fires

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ABSTRACT

Non-Boussinesq plumes have many engineering applications. One of them is in the field of fire simulation. The subject has been studied extensively. However, the entrainment under high density difference is not yet clearly understood. The study intends to address the problem and produce a plume model for compartment fire simulations.

The project contains two parts. In the first part, plume tests in the non-Boussinesq range were performed. For pure jets, the decay constant for the mean centreline velocity k_{jw} , and the velocity width constant k_{jwg} were measured to be 6.369 and 80.4 respectively. The mean centreline concentration decay constant k_{jc} was from 3.584 to 5.094. The concentration width constant k_{jcg} varied from 41.785 to 60.467. The entrainment coefficient α was found to be around 0.0516 to 0.0585. For plumes, the mean centreline vertical velocity decay constant k_{pw} , was measured to be 3.85. The velocity width constant varied from 113.2 to 229.6. A mass flux formula that takes into consideration of the density ratio and Gaussian shape profile was proposed.

In the second part of the project, exploratory field fire tests in multiple compartments were conducted. The layout and design of the compartment fire tests at NTU were dictated by the Singapore Civil Defence Force (SCDF) and Housing Development Board (HDB). Numerical software such as CFAST and FDS were used to obtain predictions and compare with the test data. Further studies are required to relate the mass flux formula obtained in the plume experiment with the field test results.

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LIST OF SYMBOLS

Symbol	Description	Unit
A_t	Total internal surface area	m^2
A_T	Boundary surface area for heat loss (excluding opening)	m^2
A_v	Vent or opening area	m^2
b	Plume width	
$b_{1/2}$	$1/2$ -width of plume or jet	m
b_v	$1/e$ -width of velocity	m
b_c	$1/e$ -width of concentration	m
B	Buoyancy flux	
B_0	Initial buoyancy flux	m^4/s^3
c	Specific heat	J/kg K
c_0	Initial concentration of the jet	$\mu\text{g/liter}$
C_d	Orifice coefficient	-
c_p	Specific heat for constant pressure, (for air, $c_p = 1.0\text{kJ/kg K}$)	kJ/kg K
c_v	Specific heat for constant volume	kJ/kg K
$\bar{c}$	Mean concentration of the jet or plume	$\mu\text{g/liter}$
$\bar{c}_c$	Mean concentration along the centreline of the jet or plume	$\mu\text{g/liter}$
D	Pool diameter	m
	Section dimension of wood sticks	m
D_0	Diameter of the nozzle	m
G	Grey scale	-
E	Internal energy	J
f_v	Ventilation factor $f_v = a_v h_v^{1/2}$	$\text{m}^{3/2}$
Fr_0	Jet initial densimetric Froude number	-
H_0	Height of compartment	m
h_c	Height of wood crib	m
H_D	Smoke layer elevation, equivalent Z_i	m
h_k	Heat transfer coefficient	$\text{kW}/(\text{m}^2\text{K})$

LIST OF SYMBOLS

HRR	Heat release rate	kW
H_v	Vent height	m
I	Local incident light intensity in the light sheet	-
I_r	Fluorescence intensity received by a light-sensitive pixel of the digital CCD camera	-
I'	fluorescence signal	-
k	Thermal conductivity	W/m°C
k_1	Proportionality constant	-
k_2	Factor for the optical arrangement	-
k_{jc}	The decay constant for the concentration of jet	-
k_{jw}	Jet decay constant	-
k_{jcg}	1/e concentration width constant	-
k_{jwg}	1/e velocity width constant	-
k_{jwh}	½ velocity width constant	-
k_M	Constant in McCaffrey plume $k_M = \frac{\bar{w}_c}{\sqrt{2gz\Delta T_c/T_0}} \sim 0.9$	-
k_P	Peak ratio for PIV peak validation	-
k_{pc}	The decay constant for the concentration of plume	-
k_{pw}	The decay constant for the velocity of plume	-
k_{pcg}	1/e concentration width constant	-
k_{pwg}	1/e velocity width constant	-
K	A constant $K = k_1 k_2 \phi \varepsilon PV$	
L	Subscript L for upper-layer	-
l_1, l_2	Depth of constant temperature layer	m
l'	Length	
L_m	Characteristic length scale of plume $L_m = \frac{M_0^{3/4}}{B_0^{1/2}}$	m
L_f	Flame length	m
L_q	$L_q = \frac{Q_0}{M_0^{1/2}}$	

LIST OF SYMBOLS

m	Momentum flux	-
M	Molecule weight	kg/mol
m_0	Initial weight of wood crib	kg
M_a	Mass flow rate	kg/s
M_0	Initial momentum flux	m^4/s^2
$\bar{M}$	Mean momentum flux	-
m_i	Mass of i-layer	kg
$\dot{m}$	Mass lost rate	kg/s
$\dot{m}''$	Mass lost rate per unit area	kg/m^2
$\dot{m}_e$	Mass entrainment rate	kg/m^2
$\dot{m}_g$	Mass outflow rate	kg/s
$\dot{m}_\infty''$	Mass loss rate per unite area for an infinite-diameter pool	kg/m^2
Nor	Normal flat configuration	-
P	Pressure	Pa
P_0	Pressure of atmosphere, $P_0 = 1.013 \times 10^5 \text{N}/\text{m}^2$	N/m^2
P_f	Fire perimeter or πD_0	m
q	Mass flow rate	kg/s
q_0	Initial mass flux	kg/s
Q_{O2}	Heat release rate measured from oxygen consumption calorimetry	kW
Q	Volume flux	m^3/s
Q_0	initial volume flux	m^3/s
r	Horizontal distance from the centreline of jet and plume	-
R	Radius of fire surface	m
R	Gas constant for air, $R = R_0/M = 287 \text{J}/(\text{kg K})$	$\text{J}/(\text{kg K})$
R_0	Universal gas constant, $R_0 = 8.314 \text{J}/(\text{mol K})$	$\text{J}/(\text{mol K})$
R_{i0}	Richardson number	-
S	Spacing of wooden stick of wooden crib	m
s	Enthalpy	kJ
s_l	Distance along the direction of propagation of the incident laser beam	-

LIST OF SYMBOLS

s'	Distance along the direction of propagation of the emitted fluorescence beam	-
t	Time	S
T	Temperature	°C
T_0	Ambient temperature $T_0 = 29^{\circ}\text{C}$ (302.15K)	°C
T_1, T_2	Temperature of thermocouples	°C
T_a	The lower-layer temperature in compartment	°C
T_{cj}	Compartment ceiling jet gas temperature 0.10 m below ceiling	°C
T_g	The upper-layer temperature in compartment	°C
T_{gu}	Compartment upper-layer average gas temperature	°C
t_p	Thermal penetration time	sec
T_{U-CF3}	Compartment upper-layer average gas temperature, result of CFAST version 3.1.7	°C
T_{vb}	Compartment vent bulk centreline gas temperature above neutral plane	°C
$\bar{T}$	Average temperature	°C
U	Subscript U for upper-layer	-
V	Volume	M^3
v_p	Surface regression velocity, v_p for wood is $2.2 \times 10^{-6} D^{-0.6}$	$\text{m}^{-0.6}$
w_0	Exit velocity of jet or plume	m/s
$\bar{w}$	Mean axial velocity of jet or plume	m/s
$\bar{w}_c$	Centreline mean axial velocity of jet or plume	m/s
W, C, F	Walls, ceilings, and floor	-
WB	White-Block configuration	-
z	Elevation from fuel bed	m
z_0	Virtual origin	m
z_{0jw}	Virtual origin of the velocity	m
Z_i	Interface elevation, boundary between upper hot layer and lower cool layer	m
α_f	Rate of fire burning	kW/s^2

LIST OF SYMBOLS

α	Entrainment coefficient	-
β	is the reciprocal constant relating the temperature and the air density	-
γ_h	Ratio of specific heat, $\gamma_h = c_p/c_v$	-
γ	Coefficient of the power of density ratio	-
δ	Thickness of thermal boundary	m
Δ	Effective gravitational acceleration	-
ΔH_c	Heat of combustion	MJ/kg
ΔT	Temperature rise compare to ambient	°C
ΔT_c	Centreline mean temperature	°C
$\Delta \rho$	Local density difference between the plume and the ambient fluid	kg/m ³
ε	Molecular absorptivity or extinction coefficient of the dye for the incident light	-
ε'	Molecular absorptivity or extinction coefficient of the dye for emitted fluorescence beam	-
η_{jwg}	Velocity width constant of jet	-
η_{jcg}	Concentration width constant of jet	-
η_{pwg}	Velocity width constant of plume	-
η_{pcg}	Concentration width constant of plume	-
η_w	Molecular extinction coefficient of clear water for the incident laser	-
η_w'	Molecular extinction coefficient of clear water for the emitted fluorescence beam	-
ϕ	Quantum yield defined as the ratio between the emitted and the absorbed energy	-
θ	Heat release rate	kW
θ_c	Convective part of the heat released	kW
ρ	Density	kg/m ³
ρ_0	Initial density of plume or jet	kg/m ³
ρ_a	Ambient density (for air $\rho_a = 1.2\text{kg/m}^3$)	kg/m ³

LIST OF SYMBOLS

χ	Combustion efficiency	-
$k\beta$	Product of the extinction-absorption coefficient of the flame (k) and the mean-beam-length corrector (β)	m^{-1}
X''	Double quotation mark implies that the quantity is measured per unit area	-
$\dot{X}$	Dot implies that the quantity is measured per unit time	-

CHAPTER 1

INTRODUCTION

1.1 Background and Objectives

This report is separated into seven chapters. Chapters One and Two are the introduction and literature review. Chapters Three and Four contain detailed descriptions of the experimental setup, results and analyses. Chapters Five and Six show the exploratory tests on compartment fire and the case study by using the fire simulation software CFAST and FDS. The conclusion and future work are in Chapter Seven.

It is well known that fire plume modelling is one of the crucial components for fire simulation. The fire plume acts as the source and “mechanical pump” of heat and contaminated gas for the smoke layer. The accuracy of the plume predictions has a direct impact on the overall results of the fire modelling. However, the behaviours of the flames involve the mixing between two difference fluids, fuel vapour and oxygen, violence chemical reaction between them, with the releasing of tremendous heat and hot gas, and the mixing of the hot gas and the ambient gas. The mechanisms of the fire plume are rather complex because of the above mentioned phenomena.

The fire plume behaviours have been studied extensively. Various models based on plume theories and experiments have been proposed and widely used, such as the Zukoski (1980, 1994), Heskestad (1995), McCaffrey (1979) and Thomas (1963) model. These models are simple and practical, and many of the modelling software are still using them for simulations. However, the temperature inside a flame is so hot that it can easily exceed 1000°C. Thus, the smoke or hot gas plume rising from the fuel source has a temperature hovering around 600°C. Therefore, the density of the hot gas plume may

only be one third of the surrounding air, in which case the non-Boussinesq effect would become significant. The mechanisms of the mixing of hot gases in the non-Boussinesq range are not yet fully understood.

The current project aims to improve the understanding of the mixing behaviour in the non-Boussinesq range. The thesis consisted of two parts. The first part was to study the entrainment of non-Boussinesq plumes under laboratory conditions. Two fluids, namely ethanol and calcium chloride solutions, with high density differences were employed in the experiments. The plume was generated by releasing an ethanol solution from the bottom to the calcium chloride ambient. The plumes characteristics were recorded by Particle Image Velocity (PIV) and Planer Laser Induced Fluorescence (PLIF) techniques. PIV is the technique of using high speed camera to record the particle movement and velocity of a fluid flow. While PLIF is a similar technique but what it record is the light intensity or the concentration of the dye. The results provided useful data for the study of the density difference and entrainment relationships. The improved understanding on the non-Boussinesq behaviour will be useful for future fire or smoke simulations.

The second part of the project included an exploratory study on compartment fire. It was consisted of two field tests; both were conducted to understand the instrumentation for fire tests. Two residential units with different compartment boundary conditions were tested under fire. The temperature of the smoke and the elevation of smoke layer were recorded at various locations.

The field test results were simulated using CFAST (Jones et al., 2000), a zone model, and FDS (McGrattan et al., 2001), a field model. Both were sophisticated enough to model complex compartment fires. CFAST is a zone model program, which separates a compartment into a few homogeneous zones for fire simulation. The field model, FDS, on the other hand, separates the entire simulation field into small space for detail prediction of gas flow. The experimental data from the compartment fire tests were compared to the results generated by CFAST and FDS. The differences in predictions

were shown and discussed. The initial intention of the project was to produce a fire plume model that incorporates the non-Boussinesq effects. The new model can then be implemented into CFAST source code for fire simulations. Comparisons could then be made of the temperature, smoke layer height, velocity of hot layer, etc, between fire plumes with and without Boussinesq assumption. The numerical results could also be compared with the fire test data for validation. Due to time constraint, the comparison could not be carried out in time.

CHAPTER 2

LITERATURE REVIEW

2.1 Studies of Jets in a Stagnant Ambient Fluid

Jets have wide applications in many engineering fields, such as car engine, airplane, rocket, etc. They have been studied over the past century. The research has matured to a stage that the predictions of jets become well established. A general review of previous studies of jets is presented in this chapter.

The most simply form of jet is fluid come out of a round circular nozzle with constant and stable velocity. The moving fluid will mix with the ambient fluid and becomes a jet. The jet can be separated into two zones, the Zone of Flow Establishment (ZFE) and Zone of Established Flow (ZEF). The ZFE is the portion that starting from just downstream of the nozzle. Because the ambient fluid is not yet able to penetrate to the centre of the jet, the centreline velocity remains constant. Following the ZFE is the ZEF. Here the centreline velocity will decrease as it goes further downstream. However, the velocity profiles of the jet remain the shape of Gaussian.

The analytical methods for both jets and plume can be broadly classified into three groups: dimensional analysis, integral analysis and turbulence modelling. Dimensional analysis is a powerful tool for fluid mechanics as it can identify the significant parameters for flow processes. Majority of them are based on the characteristic length scale. However, the relationships between two dimensionless groups need to be obtained by other means.

In the method of integral analysis, the equations of motion (continuity, Navier-Stokes and scalar advection-diffusion equations) are integrated across the cross-section of buoyant jets. Conservation of momentum, buoyancy and species are derived. The jet

flow is typically assumed to be self-similar, while the distributions of velocity, buoyancy concentration in a cross-section are assumed to be Gaussian shapes. The Boussinesq approximation, which is based on density variation, is commonly applied. The system of equation requires a closure equation, the most common of which are the entrainment assumption and the spread assumption.

The most commonly used turbulent model for buoyant jets is the k - ε model and large eddy simulation. The turbulent shear stresses are modelled to close the system of governing equations. Computations are extensive for turbulent modelling and most of the studies require the use of computer.

The flow of a turbulent round jet has been studied by many researchers. In the zone of established flow of a self-preserving turbulent jet, the mean axial velocity along the jet's centreline is decreasing as it goes further downstream. It is given by:

$$\frac{w_0}{\bar{w}_c} = \frac{1}{k_{jw}} \left(\frac{z}{D_0} - \frac{z_{0jw}}{D_0} \right) \quad (2.1)$$

where z is the distance away from nozzle, w_0 is the jet exit velocity, $\bar{w}_c$ is the local centreline mean axial velocity, k_{jw} is the jet decay constant, z_{0jw} is the virtual origin of the velocity and D_0 is the diameter of the nozzle.

Similarly, the mean concentration decay along the jet's centreline can be described by:

$$\frac{c_0}{\bar{c}_c} = \frac{1}{k_{jc}} \left(\frac{z}{D_0} - \frac{z_{0jc}}{D_0} \right) \quad (2.2)$$

where c_0 is the initial concentration of the jet, $\bar{c}_c$ is the mean concentration along the centreline of the jet, and k_{jc} is the decay constant for the concentration of jet flow.

Fiedler (1969) used different decay constants and virtual origins to describe jets, which were 5.7 and $3D_0$ for $z/D_0 < 50$, and 5.6 and $7D_0$ for $z/D_0 > 50$ respectively

Wyganski and Fiedler (1969) were unable to identify a consistent centreline decay rate between 20 and 100 diameters. However, they did note that the mean velocity profiles collapsed over this range. They concluded that, 'The rate of jet growth is sensitive to conditions of self-preservation, while the shape of the normalized velocity profile is not'. The first-order momentum, which is contributed by the integration of the mean velocities and mass fluxes of each point, is about 69% of the source momentum, based on their half-width constant of 0.086.

$$\bar{w}(z, r) = \bar{w}_c e^{-k_{jwh} \left(\frac{r}{b_{1/2}} \right)^2} \quad (2.3)$$

where k_{jwh} is the Gaussian curve fit constant and $b_{1/2}$ is the half-width.

Rodi (1975) used hot wires for measurement and obtained a constant decay rate of k_{jw} close to be 5.9.

Rajaratnam (1976) presented a detailed treatment of the mean flow characteristics of incompressible turbulent jets for use by engineers. Typical experimental results based on similarity of the root-mean-square of the velocity fluctuations and turbulent shear-stress profiles were presented.

Papanicolaou and List (1988) obtained the value of 6.711 for the decay rate, k_{jw} , and -2.56 for z_0/D_0 in pure jets. The 1/e-velocity width had the following form:

$$\frac{b_v}{D_0} = 0.104 \left(\frac{z}{D_0} + 2.58 \right) \quad (2.4)$$

The width constant, k_{jwg} was measured to be 93 for $z/D_0 > 50$, and 80 for $z/D_0 < 50$. The mean centreline concentration decay constant, k_{jcg} , and the virtual origin, z_0/D_0 , were 6.369 and -4.35. The expression for concentration 1/e-width was:

$$\frac{b_c}{D_0} = 0.139 \left(\frac{z}{D_0} - 2.51 \right) \quad (2.5)$$

The value for constant k_{jcg} was 52.

Hussein et al. (1994) measured a top-hat jet into a large room by using flying and stationary hot-wire (FHW and SHW) and burst-mode laser-Doppler anemometry (LDA) techniques. The velocity moments up to third order were obtained. The Reynolds number based on exit conditions was approximately 10^5 . The decay constant, k_{jw} and virtual origin, z_0 for jets was approximated to be 5.9 and $2.7D_0$, respectively. The first-order contribution to the momentum integral is 106% and 85% of the source momentum for the SHW and LDA/FHW data respectively. The entrainment coefficient is defined as the ratio between the mean radial velocity at the distance of b_v from centre line and the mean axial velocity $\bar{w}_c$:

$$\alpha = \frac{\bar{u}_e}{\bar{w}_c} = \frac{\frac{dQ}{dz}}{2\pi\rho_a b_v \bar{w}_c} \quad (2.6)$$

By knowing the entrainment coefficient, the mass flow rate could then be calculated.

2.2 Studies of Plumes

Plumes have been studied since 1960s. Plumes happen in nature due to density difference of two fluids, and they have many applications in engineering fields also, such as waste disposal system, smoke stacks, fire simulation, etc. Many researchers studied plumes based on the small density variation assumption, which is called the Boussinesq assumption. The review of some of the studies is presented here.

Ricou and Spalding (1961) reported their work on a jet from a 0.0127m diameter nozzle expanding in a box with porous walls. The porous walls were necessary to avoid the building up of the pressure in the box. The flow rate of various gas plumes were measured to obtain the entrainment coefficient. They suggested that the flow rate of the plume to be:

$$q = 0.32 \frac{z}{D_0} \left(\frac{\rho_a}{\rho_0} \right)^{1/2} q_0 \quad (2.7)$$

where ρ_a/ρ_0 is the ambient to source density ratio and q_0 is the initial mass flow rate. The equation worked well for the gas plume in their experiment, which consisted of hydrogen into air, propane or carbon dioxide into air. The entrainment velocity, which was proportional to the change of flow rate over height, was also proportional to the density ratio to the power of $1/2$. Given the same density, the equation itself suggested that the mass flow rate q of the plume was a linear function of the elevation z . This may not be the case for other fluid flows.

Morton et al. (1965) developed an integral model of fire plume based on the entrainment assumption that the horizontal velocity of entrained air is proportional to the mean vertical velocity. The width of the plume is also proportional to the elevation from the virtual origin.

George, Alpert & Tamanini (1977) measured the mean and turbulent quantities of velocity and temperature in a plume using hot-wire anemometry. It was found that the turbulent part of heat transfer was about 15% of the total. They also described a technique to determine the virtual origin from the plume data.

Papanicolaou and List (1988) measured the axial and radial velocity components and the concentration of a Rhodamine 6G dye simultaneously in a turbulent buoyant jet, using laser-Doppler anemometry and laser-induced-fluorescence (LIF). They concluded that the flow behaves like a jet for $z/L_m < 1$ and like a plume for $z/L_m > 5$, where L_m is the characteristic length scale defined as:

$$L_m = \frac{M_0^{3/4}}{B_0^{1/2}} \quad (2.8)$$

For $1 < z/L_m < 5$, there is a smooth transition from jets to plumes as the slope of the lines fitted to the logarithmic data changes from zero to $\pm 2/3$. The velocity and concentration profile widths ($1/e$) were expressed to be the function of z/L_m :

$$\frac{b_v}{L_m} = 0.105 \left(\frac{z}{L_m} \right) \quad (2.9)$$

$$\frac{b_c}{L_m} = 0.112 \left(\frac{z}{L_m} \right) \quad (2.10)$$

On average, the width ratio between the concentration and velocity profiles was 1.194. The rate of entrainment or the entrainment coefficient for jets and plumes were 0.0545 and 0.0875, respectively. The turbulent properties were also measured in their work.

Shabbir and George (1994) reported a comprehensive set of hot-wire measurements of a round buoyant hot air plume. The ambient temperature of the experiment was carefully measured and documented to avoid the effect of stratification. For round plumes in a neutral environment, the mean vertical velocity and effective buoyancy acceleration were given by:

$$\bar{w}_c = \frac{1}{3.4} B_0^{1/3} \left(\frac{z}{L_m} \right)^{-1/3} \quad (2.11)$$

and

$$\frac{g\beta\Delta T_c z M_0^{1/2}}{B_0} = 9.4 \left(\frac{z}{L_m} \right)^{-2/3} \quad (2.12)$$

where β is the reciprocal constant relating the temperature and the air density, and ΔT_c is the centreline mean temperature. They obtained the decay rate for centreline temperature and centreline velocity k_{pc} to be 9.4 and k_{pw} to be 3.4, respectively, and the width constant, k_{pwg} and k_{pcg} to be 68 and 58, respectively.

Hunt and Kaye (2001) investigated the location of the asymptotic virtual origin of positive buoyant turbulent plumes. The plumes were generated from a horizontal source of finite area. An analytical expression for the location of the asymptotic virtual source relative to the actual source of the plume is developed. The plume conservation equations were solved for the volume flow rate, and the position of the asymptotic virtual origin was deduced from the scaling of the volume flow rate at a large distance from the source. The virtual origin was found to be a function of the source parameter $Q_0^2 B_0 / M_0^{5/2}$, which represented the relative importance of the initial fluxes of buoyancy B_0 , momentum, M_0 , and volume Q_0 .

Rooney and Linden (1996) re-examined the problem of natural ventilation of a room fire and obtained expressions for the depth and density of the homogenous ceiling layer. The model was compared to the test data.

In order to derive a solution for non-Boussinesq plume, Rooney and Linden (1997) obtained the similarity solutions for the mean vertical velocity w , radius b and reduced gravity Δ

$$w = LF^{1/3} (z - z_0)^{-1/3} \quad (2.13)$$

$$b = M(z - z_0) \left(\frac{\bar{\rho}_c}{\rho_a} \right)^\gamma \quad (2.14)$$

$$\Delta = \frac{\Delta \rho_p}{\rho_a} g = NF^{2/3} (z - z_0)^{-5/3} \quad (2.15)$$

where $(z - z_0)$ is the height above the virtual origin, F is the conserved quantity with the units of buoyancy flux, γ is negative $1/2$. L , M and N are constants related to each other and to the entrainment coefficient α by

$$N/L^2 = 4/3 \quad (2.16)$$

$$LM^2N = 1/\pi \quad (2.17)$$

$$M = 6\alpha/5 \quad (2.18)$$

so that

$$N^{-1} = \pi^{2/3} (6\alpha/5) \left(\frac{10}{9\alpha} \right)^{-1/3} \quad (2.19)$$

They concluded that the fire plume may not be Boussinesq in nature until it reaches a height of several flame lengths above the source. The mass flux in the plume was given by

$$q = \int_0^\infty \rho \bar{w} 2\pi r dr = N^{-1} \rho_a \left(\frac{g\theta}{2c_p \rho_a T_a} \right)^{1/3} z^{5/3} \quad (2.20)$$

This suggests that the entrainment constant in the present model of α to be ranging from 0.124 to 0.20. The entrainment velocity is then proportional to the density ratio to the power of 0.5. Their solution is similar to that provided by Ricou and Spalding (1961).

Wang and Law (2002) did a detailed investigation into buoyant jets by applying combined DPIV and PLIF techniques. Both the time mean and turbulent mass transport were measured. The integral model of buoyant jets was refined with incorporation of second-order conservation of mass and momentum fluxes. The model employs the widely used entrainment assumption in which the entrainment coefficient was assumed to be a function of the local Richardson number. The turbulent momentum flux was treated as a fixed percentage of the local mean flux based on the experimental findings. The concentration-velocity-width ratio was presented as a function of the local Richardson number rather than a constant.

2.3 Studies of Fire Generated Plume

Fire plume is one kind of buoyant diffusion plume due to high temperature generated by the fire. However, fire plume is much more complex than normal buoyancy plume because the potential and the kinetic energy of the plume may not be conserved when the chemical reactions are involved. In the flame region, the reactions of chemical components increase the internal energy of the gases. Part of the energy will radiate or conduct away from the hot gas, while the remaining part of energy, normally about 70% of the total energy, is in the form of convection. Above the flame region, the by-products of combustion, viz. hot gas and ashes become a buoyancy plume. The temperature of the gas is high and the density of the gas is substantially lower than ambient air. The potential energy will then convert into kinetic energy, or motion of the plume. The surrounding gas is entrained into the plume, further increasing the upward flow rate of the plume. The flow behaviour in high density difference such as the case of fire plume is not yet well understood. In the case of fire taking place in a confined space, such as a

room, the hot smoke will occupy the upper portion of the room. The hot gas or smoke is virulent to the people inside the building.

Emmons, H. W. (1980) presented a general review of the common research areas on fire sciences. Fire plume was classified in the subject of gas phase phenomena. Although many of the researches had been conducted, either based on experiments or theoretical predictions, he concluded that many of the uncertainties required to be solved.

Tieszen, S. R. (2001) gave a very comprehensive review on the fluid mechanics of fire. On the part of fire plume, he focused on three areas: the flame height, the transportation characteristics of the post-combustion plume, and the entrainment into both fire and plume. He points out that, the plume growth is related to air entrainment, and its width scales linearly with distance from the source. The temperature difference between the plume centreline and the surrounding fluid is to the negative 5/3 power of the vertical distance from the source, z . The centreline velocity is proportional to the negative 1/3 power of the vertical distance from the source, z . However, the largest discrepancy comes from the temperature radius and velocity radius. The entrainment rates from different researchers are also compared in this article.

Thomas et al. (1963) found that the mass flow rate was independent of the energy release rate in the continuous flame region or the near field. However, it was a function of the perimeter of the fire and the height above the fire source. The equation of mass flow rate for Thomas et al. was particularly valid for large fire.

$$q = 0.188P_f z^{3/2} \quad (2.21)$$

where P_f is the fire perimeter or πD_0 .

McCaffrey (1979) measured the temperature and the velocity in the near field of a purely buoyant diffusion plume produced by a porous refractory burner. Thermocouples and an impact probe were employed for measurement purpose. Three distinct regimes were identified in a plume, a continuous flame region, an intermittent regime, and plume region. The continuous flame region started from the surface of the burner with zero

velocity to the top of the continuous flame. The temperature was found to be constant. The expression for elevation, velocity and temperature were:

$$\frac{z}{\theta^{2/5}} < 0.08 \quad (2.22)$$

$$\frac{\bar{w}_c}{\theta^{1/5}} = 6.8 \left(\frac{z}{\theta^{2/5}} \right)^{1/2} \quad (2.23)$$

$$\frac{2g\Delta T_c}{T_0} = \left(\frac{6.8}{k_M} \right)^2 \quad (2.24)$$

In the intermittent region:

$$0.08 \leq \frac{z}{\theta^{2/5}} \leq 0.2 \quad (2.25)$$

$$\frac{\bar{w}_c}{\theta^{1/5}} = 1.9 \quad (2.26)$$

$$\frac{2g\Delta T_c}{T_0} = \left(\frac{1.9}{k_M} \right)^2 \left(\frac{z}{\theta^{2/5}} \right)^{-1} \quad (2.27)$$

and in the plume region:

$$\frac{z}{\theta^{2/5}} > 0.2 \quad (2.28)$$

$$\frac{\bar{w}_c}{\theta^{1/5}} = 1.1 \left(\frac{z}{\theta^{2/5}} \right)^{-1/3} \quad (2.29)$$

$$\frac{2g\Delta T_c}{T_0} = \left(\frac{1.1}{k_M} \right)^2 \left(\frac{z}{\theta^{2/5}} \right)^{-5/3} \quad (2.30)$$

where $k_M = \frac{\bar{w}_c}{\sqrt{2gz\Delta T_c/T_0}} = 0.9$ for all cases, θ is the rate of heat release from fire in kW,

ΔT_c is the temperature difference along the centreline of plume axis.

The 1/e-velocity width was expressed as:

$$b_v = 0.46 \left(\frac{z}{\theta^{2/5}} \right) + 0.013\theta^{1/2} \quad (2.31)$$

The ratio between the velocity width and the temperature width was about 1.2.

Zukoski et al. (1980) captured the mass flow rate by collecting the plume gases in a hood and controlling the flow rate in the hood exhaust, where the hot gas layer height was kept constant. The ideal plume theory was adjusted slightly with the coefficient based on the experimental data.

$$q = 0.21 \left(\frac{\rho_a^2 g}{c_p T_a} \right)^{1/3} \theta^{1/3} z^{5/3} \quad (2.32)$$

where q is the mass flow of the plume, c_p is the heat capacity of air under constant pressure.

Heskestad (1984) summarized a number of engineering relations from the literature for calculating the properties of fire plume. Those plume properties included the flame heights, temperature differences, velocities, concentrations of gases, and entrainment rates. The assumption of point source was removed and the virtual origin concept was introduced.

$$z_0 = 0.083\theta^{2/5} - 1.02D_0 \quad (2.33)$$

where D_0 is the diameter of the fuel source measured in [m], and θ is the total energy release measured in [kW]. In his approach, the fire plume was separated into two parts by the mean flame height L_f , which was expressed as:

$$L_f = 0.235\theta^{2/5} - 1.02D_0 \quad (2.34)$$

Heskestad (1984) pointed out that the plume temperature and velocity were distributed according to the Gaussian curve. The non-Boussinesq condition has been considered since the expression was based on experimental data. The equations for plume radius b , centreline temperature difference ΔT_c and velocity w_c , and mass flux q above the mean flame height were:

$$b = 0.12 \left(\frac{T_c}{T_a} \right)^{1/2} (z - z_0) \quad (2.35)$$

$$\Delta T_c = 9.1 \left(\frac{T_a}{g c_p^2 \rho_a^2} \right)^{1/3} \theta_c^{2/3} (z - z_0)^{-5/3} \quad (2.36)$$

$$w_c = 3.4 \left(\frac{g}{c_p T_a \rho_a} \right)^{1/3} \theta_c^{1/3} (z - z_0)^{-1/3} \quad (2.37)$$

$$q = 0.071 \theta_c^{1/3} (z - z_0)^{5/3} + 1.92 \times 10^{-3} \theta_c \quad (2.38)$$

where θ_c is the convective part of energy, normally 70% of the total heat released.

The large density differences were taken into account by the term (T_c/T_a) in equation (2.35). Since the Ideal-Gas-Law:

$$PV = nRT \quad (2.39)$$

Therefore,

$$T_c/T_a = \rho_a/\rho_c \quad (2.40)$$

The width of the fire plume was proportional to the density ratio (ρ_a/ρ_c) to the power of $1/2$.

The mass flux below the mean flame height was given to be:

$$q = 0.0056 \theta_c \frac{z}{L_f} \quad (2.41)$$

CHAPTER 3

EXPERIMENTAL EQUIPMENT AND TECHNIQUES

3.1 Introduction

The objective of this experiment was to find out the velocity and density distributions of a non-Boussinesq buoyant plume, and hence the entrainment function. The difference in densities was modelled by using ethanol and calcium chloride solutions with matched refraction indexes. Two CCD cameras (Charge Coupled Device) were employed to capture the dye concentration images and the seeding particles by techniques of PLIF (Planar Laser Induced Fluorescence) and DPIV (Digital Particle Image Velocimetry). The information of densities and velocities of the flow fields were extracted from the raw images.

The experiments were conducted in an air-conditioned room in the Hydraulic Modelling Laboratory, School of Civil and Environmental Engineering (CEE).

3.2 Experimental Setup for the Plume Tests

The physical setup for the non-boussinesq buoyancy plume experiments is shown in *Figure 3.1*.

The experiments were conducted in a glass test tank with a dimension of $0.55\text{m} \times 0.55\text{m} \times 1.2\text{m}$ (height). The tank was constructed with glass panels and a stainless steel frame, which bore the weight of the fluid. The thickness of the glass panel was 1.5cm. The glass tank, together with the stainless steel frame, was placed on a stainless steel table, 0.5m high.

Figure 3.1 Schematic diagram of the physical setup for non-Boussinesq plume test

There were three holes, with one-inch diameter drilled onto one of the four vertical glass panels, two at the lower right corner and one at the top left corner. The holes were fitted with ball valves and used as either inlets or outlets. The distances between the edge and the centres of holes were 10cm. The top hole was used to release the overflow fluid to the discharging tank and maintain the constant fluid level inside the tank. One of the two bottom holes was used as an inlet of the source fluid, and the other (not shown on Figure 3.1) was used to drain out the fluid after testing.

The advantages of this experimental set-up were low cost and saving on laboratory space, since all the holes were manufactured on the same glass panel. However, there was always 10cm fluid left in the tank when the fluid was drained out. Two hoses, with 20mm and 5mm in diameter, were used to siphon out the remaining fluid.

The source solution was discharged from a nozzle, which was seated at the bottom of the tank. The nozzle was 100mm in length and had a diameter of 7.5mm. It was welded onto a stainless steel plate, which was held to the bottom panel by yellow adhesive tape. The nozzle was slightly out of alignment due to manufacturing

imperfection. The effects of this error are shown in the plot of velocity width or concentration width such as *Figure 3.2*. The angle of the nozzle estimated from the centreline location was around 1.4° . The nozzle was connected to the inlet hole through valve 2 by a flexible hose and a fitting. This design allowed the change of nozzle head for future experiment.

Figure 3.2 Plot of centreline of jet and velocity width ($D0Q130$)

(Curves b/D_0 and Centre were obtained from Gaussian curve fit of the cross-section, while curves b_+/D_0 and b_-/D_0 were obtained from searching the point where the value equalled to $1/e$ of the centreline)

The nozzle in this experiment was 0.1m in length. It was relatively shorter compared to the 0.3m length used in Law and Wang (2000) due to constraints in geometry. It may not be able to remove the swirl near the exit. However, the objective of this experiment was on the mean velocity and concentration of the flow. Therefore, the fluctuations of the exit did not have significant effect on the accuracy of results.

The source fluid was supplied from a constant head tank located one storey above the test tank, which was 3.2m above the ground level. The potential difference between the fluid level in the constant head tank and the glass test tank was measured to be 2.8m.

The constant head tank was made of fibre glass with a dimension of 0.3m $\times$ 0.6m $\times$ 0.5m (height). There was a diaphragm of height 0.3m in the middle of the length of the tank, which separated the tank into two chambers (0.3m $\times$ 0.3m $\times$ 0.3m high). A submersible pump was installed into one of the two chambers and continuously pumped the solution into the other during each test. The fluid would eventually fill up the second chamber, and spill over the diaphragm, and back to the first chamber. The infilling and draining became a cycle and the fluid inside the second chamber was kept at constant head. During a test, the flow rate of pump was always greater than the flow rate for the experiment, and so the second chamber would always be filled with the source solution. Therefore, the fluid level was able to maintain at a constant head, which was slightly above the diaphragm at 0.3m height.

The second chamber of the constant head tank was connected to copper pipes by a valve. The pipes were connected to a flow meter on the first floor, followed by an adjustable valve, a section of flexible hose, and finally to the inlet of the test tank. *Figure 3.3* shows some pictures of these components. There were two valves built on the flexible hose, one for releasing air and the other for flushing.

The advantage of using a constant head tank instead of a peristaltic pump for source discharge was that it could produce a much more stable flow. However, it may cause problems for the low flow rate, even with the 2.8m potential difference, because of the trapped air inside the tubes. The trapped air caused a reduction in the flow cross-section and a reduction in potential head. It was recommended to reduce the bending, especially 90° bending, as much as possible to minimize the occurrences of air trapping. The submersible pump could be replaced by a peristaltic pump. Submersible pump has a much higher flow rate but the heat generated is also tremendous. The increase in

temperature in the fluid may not be noticeable in normal situation, but detectable in the circulating case.

Figure 3.3 Pictures of the components of the experimental setup

In this study, the buoyant jet was created by discharging ethanol solution (lighter density) upward into an ambient of calcium chloride solution (heavier density). The situation was similar to the fire generated plume or ocean outfall. The results are able to describe the movement of gases because the dominant factor of entrainment is the turbulent stress.

A combined Planer Laser Induced Fluorescence (PLIF) and Digital Particle Image Velocimetry (DPIV) techniques was used for the respective measurement of concentrations and velocities of the flows. A mini Nd:YAG laser was used for illumination purpose. Two Charge Coupled Device (CCD) cameras were employed to record the instantaneous images. The PLIF and DPIV systems were coordinated, controlled, and recorded by equipment and software from Dantec Measurement Technology A/S and a normal desktop. A special chemical, Rhodamine B, was used as dye because of its fluorescence property. The fluorescence light intensity of Rhodamine B is proportioned to its concentration as well as the intensity of incidence laser. With proper calibration, the concentration of Rhodamine B was determined by PLIF technique.

The velocity vectors were calculated from the cross-correlation of two consequent images of the small particles in the fluids. The analysis toolkit was FlowMix for PLIF developed in-house in NTU and FlowManager from Dantec.

It was observed during the tests that the mixed fluid will stay afloat and form layer. The layer interface would descend very fast and reach the area of interest in a minute. This is similar to the descending smoke layer in the study of enclosure fire. The mixed fluid will attenuate the incident laser light described by Beer-Lambert law. This behaviour will be described in Section 3.5 of this chapter. However, the effects were not obvious in the PLIF images because the maximum light intensity of the images remained more or less unchanged from inspection. Therefore, the effects of descending mixed layer were ignored.

3.3 Theory of PIV

Particle Image Velocimetry (PIV) is a measurement technique for obtaining the velocity vectors based on the movement of small particles, or seeding. The technique is based on the well known and simple equation of speed equal to distance travelled divided by time taken. In PIV, the parameter that is actually measured is the distance travelled by a group of particles in the flow within a known time interval. A laser is used to generate a vertical light-sheet shining through the area of interest. A CCD camera is positioned at right angles to the light-sheet generated and is used to capture the scattered light by the illuminated seeding particles. (*Figure 3.4*)

Figure 3.4 Basic arrangement of PIV system

During the test, the laser will emit two subsequent pulses at a very short time interval in between them. With the help of optics, the laser pulses spread into a flat sheet with a thickness around 3mm that strike into the area of interest. The scattered lights of the seeding particles in the flow are captured by the CCD camera. With current available laser technology, the camera is able to record the two images separately. A standard procedure called cross-correlation is used to correlate the second image to the first one to obtain the displacement vectors.

The primary objective of cross-correlation is to correlate a group of particles in two images. The principle can be illustrated in a one-dimensional case. For example, a curve $f(x)$ moves in x -direction and becomes $u(x)$ in Figure 3.5. To determine the displacement of curve $f(x)$, a person will move it along the x -axis and find the best fit. It is obvious that the summation of the products of each point on the two curves will be maximized when $f(x)$ match $u(x)$. Therefore, the matching process is transferred to computer coding by finding the maximum summation of the product of two curves, $f(x-m)$ and $u(x)$, for different values of m along the x -axis. The calculated m value is the displacement of the curve $f(x)$.

Figure 3.5 Illustration of cross-correlation of a curve

In two-dimensional cases, the cross-correlation does the same thing. The camera images are first divided into rectangular regions called interrogation areas (IA) or interrogation regions. For each of these interrogation areas, the program will move the first-pulse-image and calculate the sum of products of every pixel with the second-pulse-image to obtain the average particles displacement vector. Doing this for all the interrogation regions produce a displacement vector map. The displacements are divided by the time interval between the two captured images to obtain velocity vectors. These are so-called raw velocity vectors.

In order to speed up the process of correlations, Fast-Fourier-Transform (FFT) algorithm is used. The captured particle images may be considered as two-dimensional signal field, analogous to a one-dimensional time series. The Fast Fourier Transformations of the two particle images are first obtained. They are then multiplied by each other. The results are inversely transformed and the peaks detected. The displacement vectors can then be obtained.

The cross-correlation will always produce results no matter what the initial input images are. Therefore, it is necessary to follow some rules of thumb to get meaningful results. The minimum number of particles within each interrogation area is five. The magnitudes of displacements are recommended to be kept below a quarter of the side of the interrogation area. The maximum velocities and the time interval between pulses are calculated based on this rule. The size of the particles should occupy five pixels in the

area. Sometimes, the PIV camera is deliberately slightly de-focused to obtain the blurred particle images for this purpose.

The vector maps produced after cross-correlation are termed raw vector maps. Some vectors are incorrect due to the noise signal, which are also termed outliers. Therefore, a few techniques provided in FlowManager are used to validate the vectors on the raw vector maps. These include Peak-height validation, velocity-range validation, and moving-average validation.

The outliers or incorrect vectors occur in almost any PIV measurement. It is important to note that there will always be an outcome whether the input is meaningful or not. The Peak-height validation verifies or rejects individual vectors based on the values of the peak heights in the correlation plane where the vector displacement was measured. In the correlation plane, there will always be the highest peak, which is hopefully to be the signal peak. This highest peak should be greater than the second-highest peak by a certain factor if it is valid:

$$\frac{\text{Highest_peak}}{\text{Second_highest_peak}} = k_p \quad (3.1)$$

This is also known as delectability criterion. It is recommended to use 1.2 for the value of k in equation (3.1) for validation. In the case of insufficient seeding particles in the images, it might be necessary to use a lower k value.

Velocity-range validation rejects vectors based on the maximum possible velocity vectors in the flow field provided by the user. The range can be calculated based on past experience, formulas provided by other researchers, the upstream conditions, criteria of displacement less than one-quarter of IA side, or any other methods. In the plume and jet experiments described here, the maximum velocity was first determined based on input from other researchers. In this experiment, the IA was assuming to be 32×32 pixels. The time interval between pulses was determined based on the maximum velocity calculated

from previous experiments. About 80% to 90% of tolerance was allowed and the time interval between pulses was reduced to the nearest hundred micro-second. The maximum velocity was then back calculated from the time interval.

Moving-average validation is based on an implicit assumption of the continuity behaviour of the flow field. It means that the velocity field is slowly changing so that there is not too much variation from one vector to its neighbourhood vector. It rejects vectors by comparing them among the neighbourhood vectors. Thus, if a vector deviates too much from its neighbourhood vectors, it must be an error vector.

3.4 Characteristics of Rhodamine B

The most commonly used fluorescent dyes are Fluorescein, Rhodamine B, and Rhodamine 6G. In this experiment, Rhodamine B was used as dye tracer for PLIF. It is a stable red or brown colour chemical. The chemical is in either powder or grain form. It has a high quantum yield and a remarkable chemical stability when exposed to laser. The wavelength of absorption is in the range from 360nm to 590nm, with the maximum absorption at 550nm. (*Figure 3.6*) The wavelength of emission is from 550nm to 680nm, with the maximum emission at 590nm. *Figure 3.7* shows an example of the emission spectrum with an excitation light at 510nm.

Rhodamine B is harmful if swallowed, inhaled, or absorbed through the skin. It is recommended to wear safety glasses and rubber gloves, and also to provide adequate ventilation when working with Rhodamine B. (Safety (MSDS) data for Rhodamine B, March 27, 2003)

Figure 3.6 Molar extinction coefficient of Rhodamine B dissolved in ethanol

Figure 3.7 Fluorescence emission spectrum of Rhodamine B dissolved in ethanol

3.5 Theories of PLIF

An ion or molecule can be excited by energy from outside, say a particular wavelength of light. Fluorescent occurs when the ion or molecule decays back into its

ground state and emits part or most of the energy absorbed. The lifetime of this process is on the order of 10ns. The number of photons emitted due to fluorescence is proportional to the number of excited molecules or ions. From a global point of view, the intensity of fluorescence light is dependent on the excitation light intensity, the concentration of dye, as well as the dye properties.

In most of the measurement in PLIF, the dye concentrations are kept low so that the weak excitation condition can be assured, to avoid no saturation and photo-bleaching phenomena from occurring. The fluorescence signal I' on a pixel of the PLIF image emitted from a small volume V of the fluid can be expressed as:

$$I'(x, z) = k_f \phi \varepsilon I(x, z) c(x, z) V \quad (3.2)$$

where ϕ is the quantum yield defined as the ratio between the emitted and the absorbed energy, ε the molecular absorptivity or extinction coefficient of the dye for the incident light, $I(x, z)$ the local incident light intensity in the light sheet, $c(x, z)$ the local dye concentration, and k_f a proportionality constant. V is a constant when the imaging window size, the camera spatial resolution and the laser sheet thickness are all fixed. In the weak excitation region, both ϕ and ε are constant. $I(x, z)$ is also fixed if the laser position, time between pulse and all other conditions remain unchanged. Therefore, the value captured in the camera is directly proportional to the concentration c .

When a laser beam travels a long distance in a dye solution, the attenuation of the laser must be considered. The decay in intensity is described by the Beer-Lambert law:

$$\frac{dI(s_l)}{ds_l} = -(\varepsilon c(s_l) + \eta_w) I(s_l) \quad (3.3)$$

where s_l is the distance along the direction of propagation of the incident laser beam and η_w the molecular extinction coefficient of clear water for the incident laser. The factor

$\varepsilon c(s)$ is the fraction of energy that is absorbed by the dye. Integrating the above equation along the travel path of the beam, say from 0 to l :

$$I(l) = I(0)e^{-\varepsilon \int_0^l c(s_l) ds_l - \eta_w l} = I_0 e^{-\varepsilon \int_0^l c(s_l) ds_l - \eta_w l} \quad (3.3)$$

where I_0 is the beam intensity at the laser source. To consider the divergence of the laser sheet, the local incident light intensity $I(x, z)$ is modelled as:

$$I(x, z) = P d(x, z) e^{-\varepsilon \int_0^l c(s_l) ds_l - \eta_w l} \quad (3.5)$$

where P is the laser power, $d(x, z)$ the planar light intensity distribution function when no absorption of energy occurs. Therefore, equation (3.2) becomes:

$$I'(x, z) = k_1 \phi \varepsilon c(x, z) V P d(x, z) e^{-\varepsilon \int_0^l c(s_l) ds_l - \eta_w l} \quad (3.6)$$

For the CCD camera, a factor k_2 is input in for the optical arrangement such as a filter. The fluorescence intensity received by a light-sensitive pixel of the digital CCD camera, I_r , can be described as:

$$\begin{aligned} I_r(m(x), n(z)) &= k_2 I'(x, z) e^{-\varepsilon' \int_0^{l'} c(s') ds' - \eta_w' l'} \\ &= k_1 k_2 \phi \varepsilon c(x, z) V_0 P d(x, z) e^{-\varepsilon \int_0^l c(s) ds - \eta_w l - \varepsilon' \int_0^{l'} c(s') ds' - \eta_w' l'} \end{aligned} \quad (3.7)$$

where $(m(x), n(z))$ is the location of a pixel in the captured image that corresponds to the (x, z) in the laser sheet, and $\varepsilon', s', l', \eta_w'$ are the respective coefficients for the emitted fluorescence beam.

The grey scale G of a pixel in the image can be described as:

$$\begin{aligned}
& G(m(x), n(z)) - G_0(m(x), n(z)) \\
&= R(m(x), n(z), I_r) k_1 k_2 \phi \epsilon c(x, z) V_0 P d(x, z) e^{-\epsilon \int_0^l c(s) ds - \eta_w l - \epsilon' \int_0^{l'} c(s') ds' - \eta_w' l'} \\
&= K R(m(x), n(z), I_r) c(x, z) d(x, z) e^{-\epsilon \int_0^l c(s) ds - \epsilon' \int_0^{l'} c(s') ds' - \eta_w l - \eta_w' l'}
\end{aligned} \tag{3.8}$$

where $R(m(x), n(z), I_r)$ is the camera response to the captured light intensity, $G_0(m(x), n(z))$ the dark level, which is the grey scale value when no photon flux is received, and the constant $K = k_1 k_2 \phi \epsilon P V$.

It was difficult to fully make use of the above equation for practical purposes. The incident laser intensity was varied from location to location. It was also difficult to account for the various travel paths and local changes of dye concentration. Therefore, the grey scale to dye concentration relationship must be built for each pixel of the CCD camera whenever there was a change in the setup.

The range of the operation region must be roughly estimated and the properties relative to the grey scale and concentration must be understood. It would be much safer and easier to have the experiment operated within the linear range of dye fluorescence, which is in the lower concentration region.

A small clear Plexiglas tank, $0.25\text{m} \times 0.1\text{m} \times 0.25\text{m}$ (high), was fabricated for calibration purpose. The thickness of the tank wall was 10mm, which insured the tank having sufficient strength to hold the weight of solution. (Figure 3.8)

Figure 3.8 Calibration tank hanged in the empty glass test tank

For calibration purpose, the Plexiglas tank was first filled with a Rhodamine B solution with known concentration and place at the area of interest. The concentration of dye was measured using a Florescence Meter, which detected the concentration based on the florescence properties of the solution. The image of the calibration was then taken with the same setup as those needed for capturing the experimental images, such as the camera aperture, size and location of the image area, laser setting etc. Normally 30 calibration images were taken each time and the averaged image was used for calibration.

If the test was in the linear region of dye concentration, two calibration images were sufficient. *Figure 3.9* shows an example of the camera responding with different dye concentrations.

Figure 3.9 Camera responses of several pixels at different concentration

(Wang, H. W. 2000)

In the experiment, the images at zero concentration and at a known concentration, say $70\mu\text{g/l}$, was taken. The dye concentration in the images collected in the experiments for each pixel, $c(m, n)$, can be modelled as:

$$c(m, n) = \frac{c_1(m, n) - c_0(m, n)}{G_1(m, n) - G_0(m, n)} \times [G_1(m, n) - G_0(m, n)] + c_0(m, n) \quad (3.9)$$

where $c_1(m, n)$ and $c_0(m, n)$ are the dye concentrations of the second and first calibration image. The value of $c_0(m, n)$ was kept to zero throughout the experiment. $G_1(m, n)$ and $G_0(m, n)$ are the grey scales of the pixels in the second and first calibration images. The $G_0(m, n)$ could be considered as background light intensity. The value $G(m, n)$ is the recorded grey scale in the experiment.

3.6 Characteristics of Calcium Chloride and Ethanol

Calcium chloride solution was used as the ambient solution in the experiment, while the light-weight ethanol solution was used as the discharged fluid injected from the bottom of the test tank. The refraction index of the two mixing fluid should be matched to each other, or the image of PIV will be distorted. Even a small difference in refraction index, say 3% of sodium chloride solution mixing with water, could result in distortion of the PIV images.

Figures 3.9 and 3.10 show how the refraction index is related to the concentration of the calcium chloride and ethanol. The two materials have similar behaviour for refraction index but different in density. For calcium chloride, a higher concentration results in higher refraction index and so does the ethanol. On the other hand, calcium chloride solution will tend to be denser but ethanol will tend to be lighter when the concentration increases. These properties allow different combinations of calcium chloride and ethanol to match the density difference and refraction index requirement.

There are five matches chosen for experiment and they are stated in Table 3.1.

Table 3.1 Matches of calcium chloride and ethanol					
Density difference	CaCl ₂ concentration	CaCl ₂ density	Ethanol concentration	Ethanol density	Refraction index
0%	0	1.0000	0	1.0000	1.3330
8%	6.3%	1.0508	21.373%	0.9667	1.3380
12%	9.3%	1.0772	33.891%	0.9370	1.3556
16%	11.3%	1.0951	37.266%	0.9199	1.3608
20%	13.0%	1.1105	69.000%	0.8700	1.3651
24%	13.3%	1.1130	80.000%	0.8336	1.3658

Figure 3.10 Refraction indexes of calcium chloride and ethanol

Figure 3.11 Densities of calcium chloride and ethanol

It was not clear whether the refraction index will change or not when the two solutions were mixed together. However, the sharp clear spots on the images showed that the refraction index was quite uniform.

Calcium chloride is commercially available as dehydrate, $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$. It is white in colour and highly soluble in water and can be used as drying agent. Therefore, it must be packed tightly using plastic bag after usage. Heat will be generated when calcium chloride is mixed with water. The temperature increase will depend on the concentration of calcium chloride. It was recorded that the temperature rose 23°C during preparation of 13% (by mass) calcium chloride solution. Therefore, it was recommended to let the solution cool down before testing began. On the other hand, the solubility of Rhodamine B in calcium chloride solution is much lower than in water. An easy way to produce calcium chloride and Rhodamine B solution is to dissolve them separately before mixing.

Ethanol has similar chemical properties when mixed with water. The energy release due to reaction with water has a peak at around 50% concentration. The maximum temperature rise recorded is approximate 5°C . Rhodamine B is highly soluble in any concentration of ethanol solution.

3.7 Procedures of Tests

The combined PIV and PLIF technique was used in the experiments. A dual-cavity mini Nd:YAG laser (Newwave Research Minilase) and two Kodak Megaplug Cameras (ES 1.0/Type 16 30Hz) were employed in the experiments. The arrangement of the test set up is shown in *Figure 3.12*.

Figure 3.12 Arrangement of equipments of the experiment

The test glass tank was placed at the corner inside an air-conditioning room. The laser and cameras were placed on two sides of the tank. The cameras were positioned at right angle to the laser sheet. Camera 2 was for PLIF purpose, and it was placed an angle to the laser sheet due to space constraint.

The preparation work for a plume test normally took half a day. Firstly, the correct amount of the calcium chloride dehydrate must be weighed. Two 1.6kg-plastic-square-buckets and a digital weighing machine were employed for this purpose. The calcium chloride was separately weighed in two buckets, the first bucket for filling the tank to 63cm, and the second for the rest of the tank. The filling of half tank was for the purpose of calibration.

For preparation of experiment, the glass tank was filled up with about 80% of the tap water. The calcium chloride powder was then put in and mixed with the water. The tank was then filled up with water to the expected volume. The solution was fully mixed. Stratification occurred because the higher concentrated calcium chloride solution tended

to occupy the bottom of the tank. The mixing of calcium chloride caused murkiness due to the air trapped in the powder, but it would become clear in a short time.

A plumb was hung and pointed to the centre of the nozzle. (*Figure 3.13*) The plumb thread was made of nylon for strength and durability. A mark was made on the thread to indicate the area of interest. The laser was turned on with lower energy level and the light sheet was created. The laser position and elevation was adjusted such that the light sheet directly strikes on the nylon thread. The laser sheet would be perpendicular to the glass panel if the reflective light sheet went through the centre of lens of laser and a single strip of light was formed on the wall.

Figure 3.13 Setting for alignment of laser and focusing of cameras

A sheet of Plexiglas with square grid line was hung next to the plumb after the alignment of laser. A ruler was attached on the Plexiglas sheet to obtain the scale factor. The PC was turned on, and so did the FlowManager processor and the cameras. The field of view could be inspected from the computer. The camera was adjusted to have the best shot of the area of interest. The image of camera 2 would be distorted slightly due to its

off-centre position. This resulted in a maximum of $\pm 5\text{mm}$ difference in position on the PLIF images.

The scale factors were obtained for both PIV and PLIF based on the ruler stuck on the Plexiglas sheet. The time interval between laser pulsing was calculated and inserted in the controlling software. The proper calibration described in Section 3.5 was followed. The glass tank was top up after calibration. Another set of calibration images for the zero-concentration case was taken.

The source fluid could be prepared in the same time. The amount of ethanol for mixing was measured and transferred to the constant head tank. A bottle of Rhodamine B solution with high concentration was prepared. The exact amount for test was measured and poured in the constant head tank. The constant head tank was then filled with water and the pump was turned on to cycle the fluid. After the dye being fully mixed, a sample was taken for concentration measurement and seeding particle was added.

In the last step of preparation, the hose was flushed with source solution and the air trapped in the hose was removed. The valve that controlled the fluid flow was adjusted for the required flow rate. Before test began, the software for controlling the laser and cameras must be set properly. On the other hand, the important parameters such as temperature and density of the source and ambient fluid were recorded down. A typical flow chart for the experiments is shown in *Figure 3.14*.

Figure 3.14 Flow chart of experimental procedure

CHAPTER 4

RESULTS AND ANALYSIS

4.1 Introduction and Objectives

The main objective of the present experiments is to obtain the mass flux of a fire plume. Beyond the flame region, fire plume is similar to any other form of plume which is a mixing between two fluids with different densities. However, due to high temperature difference, normally fire plume exceeds the normal Boussinesq range. One of the challenges is to obtain the expression for plume entrainment coefficient of fire plume in the non-Boussinesq range. In order to simplify the experiment and minimize the unknown coefficient, two fluids were used to represent the hot gas and cool ambient. In these simulations, Ethanol solutions with various concentrations were injected into the stagnant ambient created by calcium chloride solutions. The mass flux of non-Boussinesq was then obtained. The buoyancy flux would be used to link up the ethanol and fire plume, which will be discussed in section 4.9. The use of water for study of fire plumes has been conducted previously. (Clement, J. M. 2000)

The combined PLIF and PIV technique (Law and Wang, 2000) was used to obtain the data on the plume concentration and velocity. A few tests on pure round jet were first conducted to verify the experimental setup of the glass tank. The behaviour of momentum, flow rate, and entrainment coefficient were investigated. The density of the fluid was derived from the dye concentration by assuming a linear mixing behaviour. The flow rates of the plume were then calculated with the velocity and density obtained. The entrainment rates, which were the entrainment velocity over the mean maximum velocity, were derived. The diameter of the jet nozzle was fixed to be 7.5mm. The Reynolds number for pure jets ranged from 2100 to 7900.

Buoyant jet experiments were conducted in the second phase. The Reynolds number for the buoyancy jet experiments ranged from 1600 to 8700. The initial densimetric Froude numbers were between 1.7 and 12.9. The measurement locations were from the nozzle to as far as 70 diameters. The entrainment of the plume was a constant value in the region of fully developed plume. The experimental study was focused on the non-Boussinesq behaviour of the plume. However, the density differences were not significant when the location of the plume is 50 diameters away from the virtual origin. The non-Boussinesq behaviour would only have effects close to the nozzle where the dilution is small.

Mixing coming out of a nozzle has been studied in detail over the last century. There are two regions of flow for the case of neutrally-buoyant turbulent jet. Immediately after the fluid discharging into a stagnant ambient, it will flow with the same profile as it is inside the nozzle. The velocity profile inside the nozzle is a kind of pipe flow and the profile is approximately constant, if the boundary layer is not considered. Therefore, a jet coming out of an exit has uniform velocities over the cross-section.

When the fast moving centre-core fluid meets with the stagnant ambient fluid, shear force is induced due to the velocity differential. The ambient fluid is set into motion and the entrainment of the fluid occurs. In this way, the cross-section of the centre-core or potential-core of the jet is reducing and the momentum of the jet spreads into the ambient. The centre-core will disappear at the end of this region and this is the region of Zone of Flow Establishment (ZFE), which extends to 6 diameters downstream.

After the ZFE, the potential-core disappears, and the jet profiles become self-similar, in which, the shape of the velocity profiles are similar. This region is termed the Zone of Established Flow. The entrainment from the ambient will cause a continuous increase in the flow rate of the jet. However, the jet momentum remains unchanged due to the fact that external force is zero. Therefore, the velocity will reduce as the jet travels downstream.

In the case of plumes, the buoyancy force, either positive or negative, will have dominant effects on the flow behaviour. The plume momentum flux will increase or decrease due to gravity. The centreline velocities do not necessarily reduce along the travelling path of the plume.

There are some common terms used in the formulation of jet or plume problems, such as the mass flow rate, q , and momentum flux, m . They are given by:

$$q = \int_0^{\infty} \rho w 2\pi r dr \quad (4.1)$$

$$m = \int_0^{\infty} \rho w^2 2\pi r dr \quad (4.2)$$

where r is the distance from the centreline of the jet or plume, ρ and w are the local density and axial velocity, respectively. For Boussinesq plumes, the density term in the above definition is dropped for convenience and the volume flux Q , momentum flux M and buoyancy flux B , are given by:

$$Q = \int_0^{\infty} w 2\pi r dr \quad (4.3)$$

$$M = Qw = \int_0^{\infty} w^2 2\pi r dr \quad (4.4)$$

$$B = \Delta Q = \int_0^{\infty} \frac{\Delta \rho}{\rho_a} g w 2\pi r dr \quad (4.5)$$

where g is the gravitational acceleration, 9.81 m/s^2 , Δ is the effective gravitational acceleration, which is the buoyancy-generated acceleration, $\Delta \rho$ is the local density difference between the plume and the ambient fluid and ρ_a is the density of the ambient fluid.

In the case of round buoyant jets discharging vertically into a stagnant ambient, the initial volume flux, Q_0 , momentum flux, M_0 and buoyancy flux B_0 , are given by:

$$Q_0 = \frac{1}{4} \pi D_0^2 w_0 \quad (4.6)$$

$$M_0 = w_0 Q_0 = \frac{1}{4} \pi D_0^2 w_0^2 \quad (4.7)$$

$$B_0 = \Delta_0 Q_0 = \frac{\Delta \rho_0}{\rho_a} g Q_0 = \frac{1}{4} \pi D_0^2 w_0 \left(\frac{\Delta \rho_0}{\rho_a} \right) g \quad (4.8)$$

where D_0 is the diameter of the exit port, $\Delta \rho_0$ and w_0 are the initial density difference and discharge velocity, respectively

For buoyant jets, the initial part of the flow is dominated by the efflux momentum, i.e. the flow behaves like a jet. Further away from the nozzle, the additional momentum gained by the buoyancy dominates the flow. The flow then behaves in a similar way to a plume.

A length scale, L_m , given by:

$$L_m = \frac{M_0^{3/4}}{B_0^{1/2}} \quad (4.9)$$

is commonly used to describe the relative importance of momentum and buoyancy. For $z \gg L_m$, the flow behaves like a plume, and for z in the same order of L_m , the flow behaves like a jet.

There is another important characteristic length scale, L_q , defined by:

$$L_q = \frac{Q_0}{M_0^{1/2}} \quad (4.10)$$

If z is of the order of L_q , the flow is controlled by the jet exit geometry. The flow is likely to be in the Zone of Flow Establishment. On the other hand, if $z \gg L_q$, the flow rate will be much greater than Q_0 and the flow is in the Zone of Established Flow.

The ratio of the two length scales, L_q/L_m is called the jet Richardson number, R_{i0} , which is defined by:

$$R_{i0} = \frac{L_q}{L_m} = \frac{Q_0 B_0^{1/2}}{M_0^{5/4}} = \left(\frac{\pi}{4} \right)^{1/4} \frac{1}{Fr_0} \quad (4.11)$$

where Fr_0 is commonly called the jet initial densimetric Froude number. The definition of Fr_0 is:

$$Fr_0 = \frac{w_0}{\sqrt{\Delta_0 D_0}} = \frac{w_0}{\sqrt{\frac{\Delta \rho_0}{\rho_a} g D_0}} \quad (4.12)$$

Froude number describes the ratio of the inertia to buoyancy forces. In the case of pure jets, Fr_0 equals to infinity, while in the case of pure plumes, the initial momentum is zero, and the Fr_0 goes to zero.

For a non-Boussinesq plume, the plume radius is related to the density ratio of the plume and the ambient. The similarity solutions of a top-hat profile for the vertical velocity $\bar{w}$, radius b and effective gravity Δ were given by Rooney and Linden (1997):

$$\bar{w} = LF^{1/3} (z - z_0)^{-1/3} \quad (4.13)$$

$$b = M(z - z_0) \left(\frac{\bar{\rho}_c}{\rho_a} \right)^\gamma \quad (4.14)$$

$$\Delta = \frac{\Delta \rho_p}{\rho_a} g = NF^{2/3} (z - z_0)^{-5/3} \quad (4.15)$$

where z_0 is the virtual origin, $\Delta \rho_p$ is the plume density, F is a conserved quantity with the units of buoyancy flux, and L , M , and N are constants related to each other and to the entrainment coefficient α by:

$$N / L^2 = \frac{4}{3} \quad (4.16)$$

$$LM^2 N = 1/\pi \quad (4.17)$$

$$M = 6\alpha/5 \quad (4.18)$$

so that

$$N^{-1} = \pi^{2/3} (6\alpha/5) \left(\frac{10}{9\alpha} \right)^{-1/3} \quad (4.19)$$

The solution here can be converted to the far-field plume solution of fire by linking the factor F and θ .

$$F = \frac{g\theta}{2c_p\rho_a T_a} \quad (4.20)$$

The mass flux in the fire plume is then given by:

$$q = \int_0^\infty \rho \bar{w} 2\pi r dr = N^{-1} \rho_a \left(\frac{g\theta}{2c_p\rho_a T_a} \right)^{1/3} z^{5/3} \quad (4.21)$$

where ρ is the top-hat density profile. Rooney and Linden (1997) suggested that the value of γ should be negative 0.5.

If the Gaussian profiles of concentration and velocity are considered, the equations for mean centreline velocity $\bar{w}_c$, velocity width b_v , mean centreline concentration $\bar{c}_c$, and concentration width b_c are:

$$\bar{w}_c = k_{pw} B_0^{1/3} (z - z_0)^{-1/3} \quad (4.22)$$

$$b_v = \eta_{jwg} \left(\frac{\bar{\rho}_c}{\rho_a} \right)^\gamma (z - z_0) \quad (4.23)$$

$$\frac{c_0 Q_0}{z \bar{c}_c \sqrt{M_0}} = \frac{1}{k_{pc}} \left(\frac{(z - z_0)}{L_m} \right)^{2/3} \quad (4.24)$$

$$b_c = \eta_{jcg} \left(\frac{\bar{\rho}_c}{\rho_a} \right)^\gamma (z - z_0) \quad (4.25)$$

$$\frac{\Delta \bar{\rho}_c}{\rho_a} g = k_{pc} B_0^{2/3} (z - z_0)^{-5/3} \quad (4.26)$$

The Gaussian distributions of velocity, concentration, and density difference are given by:

$$\bar{w}(r, z) = \bar{w}_c e^{-\frac{r^2}{b_v^2}} \quad (4.27)$$

$$\bar{c}(r, z) = \bar{c}_c e^{-\frac{r^2}{b_c^2}} \quad (4.28)$$

$$\Delta \bar{\rho}(r, z) = (\rho_a - \bar{\rho}_c) e^{-\frac{r^2}{b_c^2}} \quad (4.29)$$

Therefore, the mass flow rate is given by:

$$\begin{aligned} q &= \int_0^\infty \bar{\rho} \bar{w} 2\pi r dr = \int_0^\infty (\rho_a - \Delta\bar{\rho}) \bar{w} 2\pi r dr \\ &= \pi \rho_a b_v^2 \bar{w}_c - (\rho_a - \bar{\rho}_c) \bar{w}_c \pi \frac{b_c^2 b_v^2}{b_c^2 + b_v^2} \end{aligned} \quad (4.30)$$

Substituting Equations (4.22) to (4.25) into Equation (4.30):

$$\begin{aligned} q &= \pi k_{pw} \eta_{pwg}^2 B_0^{1/3} (z - z_0)^{5/3} \rho_a \left(\frac{\bar{\rho}_c}{\rho_a} \right)^{2\gamma} \\ &\quad - \pi k_{pw} \frac{\eta_{pwc}^2 \times \eta_{pwg}^2}{\eta_{pwc}^2 + \eta_{pwg}^2} B_0^{1/3} (z - z_0)^{5/3} \left(\frac{\bar{\rho}_c}{\rho_a} \right)^{2\gamma} (\rho_a - \bar{\rho}_c) \end{aligned} \quad (4.31)$$

Furthermore, when Equation (4.26) is substituted into (4.31), the mass flow rate can then be expressed as:

$$\begin{aligned} q &= \pi k_{pw} \eta_{pwg}^2 B_0^{1/3} (z - z_0)^{5/3} \rho_a \left(1 - \frac{k_{pc} B_0^{2/3} z^{-5/3}}{g} \right)^{2\gamma} \\ &\quad - \pi k_{pw} \frac{\eta_{pwc}^2 \times \eta_{pwg}^2}{\eta_{pwc}^2 + \eta_{pwg}^2} B_0^{1/3} (z - z_0)^{5/3} \left(1 - \frac{k_{pc} B_0^{2/3} z^{-5/3}}{g} \right)^{2\gamma} \left(\frac{k_{pc} B_0^{2/3} z^{-5/3}}{g} \rho_a \right) \end{aligned} \quad (4.32)$$

Since the equations for top-hat profile and Gaussian profile are describing the same phenomenon, the two groups of expressions must be comparable. In order to do that, some quantities must be common. We could equal the either the mass flow rate or volume flow rate of the expressions of top-hat and Gaussian profile to find out the relationships of plume width, velocities, or temperature. The details are lengthy and not shown here. The variable γ is directly related to the density of the flow. In the non-Boussinesq range, the density difference is large and that affect the results basically from the coefficient of γ . From previous researchers, the value of γ is negative $1/2$.

4.2 Mean Velocity Profile of Jets

In the Zone of Established Flow of jets, the decay of mean axial velocity along the centreline is inversely proportional to the distance from the nozzle. The following equation is well observed in many studies:

$$\frac{w_0}{\overline{w}_c} = \frac{1}{k_{jw}} \frac{z}{D_0} \tag{4.33}$$

where $\overline{w}_c$ is the mean centreline axial velocity, k_{jw} is the decay constant, and z is the distance away from the nozzle. For measurements close to the exit, the geometry of the nozzle is important. The concept of virtual origin is established in the following form which is represented by the symbol z_{0jw} .

$$\frac{w_0}{\overline{w}_c} = \frac{1}{k_{jw}} \left(\frac{z}{D_0} - \frac{z_{0jw}}{D_0} \right) \tag{4.34}$$

The measurements of centreline mean axial velocity are shown in *Figure 4.1*. The test conditions are listed in *Table 4.1*. The virtual of origin, z_{0jw} , is zero. The average value for k_{jw} is 6.369, which is comparable to a value of 5.8 to 6.7 reported in the literature (Wang 2000). The range of measurements was from $50D_0$ to $70D_0$.

Table 4.1 Summary of tests conditions

	w_0 (m/s)	c_0 (µg/s)	Re	z/D_0
N0Q070	0.440	751	3300	50~70
N0Q080Re	0.500	777	3750	50~70
N0Q080	0.546	819	4096	50~70
N0Q130	0.869	819	6520	50~70
N0Q170	1.070	900	8025	50~70

Figure 4.1 shows that the centreline mean axial velocity of the pure jet is inversely proportional to the distance from the nozzle.

Figure 4.1 Mean centreline axial velocities of water jets

The cross-sectional distribution of velocities of a jet or plume follows Gaussian shape. Therefore, the velocity width, b_v , is normally defined as the distance away from the centreline where the mean velocity drops to $1/e$ of the mean centreline velocity. The width definition can also be applied to the concentration profile.

$$\bar{w}(z, r) = \bar{w}_c e^{-\left(\frac{r}{b_v}\right)^2} \quad (4.35)$$

or

$$\bar{w}(z, r) = \bar{w}_c e^{-k_{jwg} \left(\frac{r}{z}\right)^2} \quad (4.36)$$

k_{jwg} is the constant for Gaussian shape and the relationship between b_v and k_{jwg} is:

$$\frac{b_v}{z} = \left(\frac{1}{k_{jwg}} \right)^{1/2} \quad (4.37)$$

The velocity widths for jets are shown in Figure 4.2. The widths are linearly proportional to the distance from the nozzle. The data are compared with the results from Wang (2000) in the figure. Current results suggest that the jet width is:

$$b_v = 0.112z \quad (4.38)$$

The constant, k_{jwg} , is 80.4, which is similar to that obtained by Papanicolaou and List (1988).

Figure 4.2 Variation of Velocity width of pure jets with distance

The jet maintains its total momentum flux as it travels downstream because the external forces are balanced. Therefore, the momentum flux can serve as a check for the accuracy of the data obtained. From Equation (4.2), the momentum over a cross-sectional area is:

$$M = \int_0^\infty \overline{\rho w^2} 2\pi r dr \quad (4.39)$$

For jets, the ambient density is the same as the jet density.

$$\bar{M}(z) = \int_0^\infty \rho_a \overline{w^2} 2\pi r dr \quad (4.40)$$

With the velocity replaced by Equation (4.41), the above equation becomes:

$$\bar{M}(z) = \int_0^\infty \rho_a \left(\bar{w}_c e^{-k_{jwg} \left(\frac{r}{z} \right)^2} \right)^2 2\pi r dr = 2\pi \rho_a \bar{w}_c^2 \int_0^\infty e^{-\frac{2k_{jwg}}{z^2} r^2} r dr \quad (4.41)$$

Integrating the right hand side of the equation yields:

$$\bar{M}(z) = \pi \rho_a \bar{w}_c^2 \frac{z^2}{2k_{jwg}} \quad (4.42)$$

The initial momentum is:

$$M_0 = \frac{\pi \rho_0 w_0^2 D_0^2}{4} \quad (4.43)$$

Therefore, the ratio of momentum at various elevations to the initial momentum can be obtained:

$$\frac{\bar{M}(z)}{M_0} = \frac{2z^2 \bar{w}_c^2}{w_0^2 D_0^2 k_{jwg}} \quad (4.44)$$

From Equation (4.33), the centreline velocity can be expressed in the following way:

$$\bar{w}_c = \frac{k_{jw} w_0 D_0}{z} \quad (4.45)$$

Hence, the momentum ratio becomes:

$$\frac{\bar{M}(z)}{M_0} = \frac{2k_{jw}^2}{k_{jwg}} \quad (4.46)$$

Figure 4.3 shows the momentum ratio based on the centreline axial velocities and the Gaussian constants of velocity width at every elevation. A majority of the ratios is within 0.8 and 1.2. The results were considered reasonable and the maximum error was $\pm 20\%$.

Figure 4.3 Plot of the ratio of jet cross-section momentum to initial momentum

Table 4.2 shows the constants associated with the velocity profile obtained by other researchers. The momentum ratios were calculated based on Equation (4.46). They were slightly greater than those from other experiments. Nevertheless, the values were close to unity as expected.

Table 4.2 Comparison of velocity constants and momentum ratio in jets

	k_{jw}	z_{0jw}	$k_{jwg}(\eta_{jwg})$	z/D	Re	$\frac{\bar{M}(z)}{M_0}$
Wang 2000 PSDAJ1	6.477 (6.748)	0 (-2.493)	89.55(0.106)	40~80	12700	0.937
Wang 2000 PSDAJ3~5	6.406 (6.645)	0 (-1.013)	91.38(0.105)	15~43	6000	0.898
P1984, PL1988	6.711	-2.56	80($z/D < 50$)(0.112) 93($z/D > 50$)(0.104)	24~110	2460~ 10900	1.126
P & L	6.061	0	75.2(0.115)	30~160	11000	0.969
HCG	5.8	(15< 4 $z/D < 100$)	88.22(0.106)	70	95500	0.977
W & L	6.667	0	—	17~27	16000	—
W & L	6.289	0	—	17~27	5500	—
Fischer et al. (1979)	6.2±0.1	0	87.3 (0.107±0.003)	—	—	0.881
Chen & Rodi (1980)	6.2	0	94 (0.103)	—	—	0.818
<i>Present study</i>						
N0Q070	6.711	0	79.15	50~70	3300	1.138
N0Q080Re	6.293	0	79.01	50~70	3750	1.002
N0Q080	6.238	0	72.93	50~70	4096	1.067
N0Q130	6.443	0	88.00	50~70	6520	0.943
N0Q170	6.250	0	72.93	52~70	8025	1.071

Note: P1984: Papanicolaou (1984); PL1988: Papanicolaou and List (1988); P & L: Panchapakesan and Lumley (1993); HCG: LDA measurements of Hussein et al. (1994); W & L: Weisgraber & Liepmann (1998).

4.3 Mean Concentration Profiles of Jets

The dye concentration indicates the spreading rate of scalar quantities due to the effect of turbulent mixing. In these experiments, all the jets were turbulent in nature. Therefore, the turbulent mixing was the dominant factor.

The results of PLIF were obtained and the calibrations were conducted by using Flowmix, which is a software developed in-house in NTU. One of the PLIF image for the experiment N0Q130 is calibrated and shown in *Figure 4.4*. The image represents an instantaneous snapshot since the laser was able to freeze the flow in a few nano-seconds.

*Figure 4.4 Instantaneous Image of dye fluorescence from PLIF
(N0Q130 after calibration)*

The concentration decay of dye along the centreline of the jet can be modelled by:

$$\frac{c_0}{\bar{c}_c} = \frac{1}{k_{jc}} \left(\frac{z}{D_0} - \frac{z_{0jc}}{D_0} \right) \quad (4.47)$$

or

$$\frac{c_0}{\bar{c}_c} = \frac{1}{k_{jc}} \frac{z}{D_0} \quad (4.48)$$

where c_0 is the initial concentration, $\bar{c}_c$ is the mean concentration along the centreline, and k_{jc} is the decay constant for the concentration.

Figure 4.5 shows the centreline concentration decay of water jet comparing with the results from Wang (2000). The slopes of N0Q070 and D0Q080Re are different from the rest of the curves. The reason might be due to the imperfect alignment of the laser sheet with the centreline. Therefore, instead of the concentration of the centreline, the concentrations were that of an inclined line. The centreline concentration decay constant k_{jc} was not calculated for these two tests.

The concentrations of N0Q080 and N0Q170 were low compared with the other results. This might be due to the fact that the supply hose was not fully flushed in the two tests. The source solution was mixed with fresh water before entering into the glass tank. Hence, the concentrations were lower in the two tests. The decay constant, k_{jc} , obtained from the best fit of the data points was 5.094 for Experiment N0Q130. This was similar to that obtained by Wang (2000). For N0Q080 and N0Q170, the decay constant was 3.584 and 3.737, respectively.

Figure 4.5 Mean centreline concentration of water jets
(D0Q070 $c_0 = 751.6\mu\text{g/l}$, D0Q080Re $c_0 = 777.3\mu\text{g/l}$, N0Q080 $c_0 = 819.4\text{g/l}$, D0Q130 $c_0 = 819.4\mu\text{g/l}$, D0Q170 $c_0 = 819.4\mu\text{g/l}$)

The widths of the concentration profiles and the resulting provided by Wang (2000) are shown in Figure 4.6. The concentration width shows very close to the results obtained by Wang (2000) except for one set of data N0Q080. The Gaussian constants for the experiments are range from 41.793 to 60.466, as shown on Table 4.3.

Figure 4.6 Concentration widths of water jets

Since there was no external source of dye, the flow over a cross-section should be conserved. The mass flux of dye can be expressed as:

$$Q_c = \int c w dA \quad (4.49)$$

Since the distributions of concentration and velocity are of Gaussian shapes, the mass flux of dye becomes:

$$\overline{Q}_c(z) = \int_0^\infty \overline{c}_c \overline{w}_c e^{-k_{jcg} \left(\frac{r}{z}\right)^2} e^{-k_{jwg} \left(\frac{r}{z}\right)^2} 2\pi r dr \quad (4.50)$$

Integrating yields:

$$\overline{Q}_c(z) = 2\pi \overline{c}_c \overline{w}_c \int_0^\infty e^{(-k_{jwg} - k_{jcg}) \left(\frac{r}{z}\right)^2} r dr = \pi \overline{c}_c \overline{w}_c \frac{z^2}{(k_{jwg} + k_{jcg})} \quad (4.51)$$

On the other hand,

$$Q_{c0} = \frac{\pi}{4} D_0^2 c_0 w_0 \quad (4.52)$$

Hence, the ratio of mean dye mass flux over a cross-section to the initial mass flux of dye will be:

$$\frac{\overline{Q}_c(z)}{Q_{c0}} = \frac{4\overline{c}_c \overline{w}_c z^2}{(k_{jwc} + k_{jwg}) D_0^2 c_0 w_0} \quad (4.53)$$

The total mass flux of dye is equal to the mean dye mass flux plus the turbulent mass flux (Wang, 2000)

$$2\pi \int_0^\infty (\overline{wc} + \overline{w'c'}) r dr = c_0 Q_0 \quad (4.54)$$

Wang (2000) showed that about 7% of the total dye mass flux is carried by the turbulence in jets. Therefore, the mean dye mass flux should be conserved and the mass flux ratio shown in Equation (4.55) should be around 0.93.

Equation (4.56) can be further simplified by substituting in the expression of centreline concentration and velocity decays.

$$\frac{\overline{Q}_c(z)}{Q_{c0}} = \frac{4k_{jc} k_{jw}}{(k_{jwc} + k_{jwg})} \quad (4.57)$$

The ratios between the mass fluxes of dye at any elevation over the initial mass flux of dye calculated based on Equation (4.53) are shown in *Figure 4.7*. Theoretically, the mass flux at any elevation should be the same as the original mass flux. The ratio between them should be around unity. However, the mass flux of N0Q080Re was decreasing toward the downstream. That could be explained by mis-alignment of laser sheet. This is because the further away from the centre, the lower would be the concentration. The same happens to D0Q070. For the case of N0Q080 and N0Q170, the results would be much better if the concentration of the original decreased. Therefore, it is strongly felt that the source fluid was diluted by water. The comparison of the dye mass flux ratio obtained by other researchers is shown in *Table 4.3*. The mass flux ratio for the present study was calculated based on Equation (4.55).

Figure 4.7 Plots of mass flux of dye over the initial mass flux

Table 4.3 Comparison of dye mass flux ratio

	k_{jw}	k_{jwg}	k_{jc}	k_{jcg}	$\frac{\overline{Q}_c(z)}{Q_{c0}} = \frac{4k_{jc}k_{jw}}{(k_{jwc} + k_{jwg})}$
Wang (2000)	6.477	89.55	5.263	59.655	0.914
P1984, PL1988	6.711	80	5.382	65.017	0.996
Fischer et al. (1979)	6.2	87.3	4.96	62	0.824
Chen & Rodi (1980)	6.2	94	5	54	0.837
<i>present study</i>					
D0Q070	6.711	79.15	-	51.466	-
D0Q080Re	6.293	79.10	-	58.906	-
N0Q080	6.238	72.93	3.584	41.783	0.780
N0Q130	6.443	88.00	5.094	55.196	0.917
N0Q170	6.250	72.93	3.737	60.466	0.700

4.4 Discussion on the Entrainment coefficient of Jets

When a jet is injected into a stagnant ambient fluid, the velocity difference between the fast moving fluid and the stable ambient generates a shear force. The shear force will bring the ambient fluid into motion. Therefore, the ambient fluid is entrained into the flow of jet and becomes part of the jet flow. Many of the integration models derived are based on this concept, which is called the entrainment of fluid. In laminar flows, the shear force is due to the viscosity of the fluid. However in turbulent flows, the force is mainly due to turbulence.

As shown in *Figure 4.4*, the actual flow contained many different eddies and vortices. There was no defined boundary for the fluid to enter into the jet. Therefore, the calculations of entrainment coefficient were based on the concept of mass conservation:

$$\frac{dQ}{dz} = 2\pi\rho_a b_v \bar{u}_e \quad (4.58)$$

where $\bar{u}_e$ is the horizontal entrainment velocity of fluid.

The flow rate of the jet can be evaluated from the experimental data defined by:

$$Q = \int_0^\infty \bar{w}(r, z) \cdot 2\pi r dr = \int_0^\infty \bar{w}_c e^{-k_{jwg} \left(\frac{r}{z}\right)^2} \cdot 2\pi r dr \quad (4.59)$$

Integrating yields:

$$\bar{Q}(z) = \pi \bar{w}_c \cdot \frac{z^2}{k_{jwg}} \quad (4.60)$$

Therefore, the differential with respect to the elevation of the flow rate becomes:

$$\frac{d\bar{Q}(z)}{dz} = 2\pi\rho_a \bar{w}_c \cdot \frac{z}{k_{jwg}} + \pi\rho_a \frac{z^2}{k_{jwg}} \frac{d\bar{w}_c}{dz} \quad (4.61)$$

From Equation (4.33), the term $\frac{d\bar{w}_c}{dz}$ can be expressed as:

$$\frac{d\bar{w}_c}{dz} = \frac{-k_{jw} D_0 w_0}{z^2} \quad (4.62)$$

Therefore,

$$\frac{d\bar{Q}(z)}{dz} = \frac{\pi \rho_a \bar{w}_c z}{k_{jwg}} \quad (4.63)$$

This equation implies the expression of horizontal entrainment velocity to be:

$$\bar{u}_e = \bar{w}_c \cdot \frac{z}{2b_v k_{jwg}} \quad (4.64)$$

Since the velocity width, elevation, and the Gaussian constant are related by:

$$b_v = \frac{z}{\sqrt{k_{jwg}}} \quad (4.65)$$

As defined in Equation (2.6), the entrainment coefficient, α , is:

$$\alpha = \frac{\bar{u}_e}{\bar{w}_c} = \frac{z}{2b_v k_{jwg}} = \frac{z}{2 \frac{z}{\sqrt{k_{jwg}}}} = \frac{1}{2\sqrt{k_{jwg}}} \quad (4.66)$$

Therefore, in case of jet, the entrainment coefficient is proportional to inverted square root of velocity width constant. In the case of plume, the expression is similar.

The entrainment coefficients from the experiments are tabulated in *Table 4.4*. The value of α was around 0.0533 to 0.0585.

Table 4.4 Comparison of entrainment coefficients

	z/D	Re	k_{jwg}	A
Wang 2000 PSDAJ1	40~80	12700	89.55	0.0528
Wang 2000 PSDAJ3~5	15~43	6000	91.38	0.0523
P1984, PL1988	24~110	2460~10900	80($z/D < 50$) 93($z/D > 50$)	0.0559
P& L	30~160	11000	75.2	0.0518
HCG	70	95500	88.22	0.0577
Fischer et al. (1979)	—	—	87.3	0.0532
Chen & Rodi (1980)	—	—	94	0.0535
<i>present study</i>				
D0Q070	50~70	3300	79.15	0.0562
D0Q080Re	50~70	3750	79.01	0.0563
N0Q080	50~70	4096	72.93	0.0585
N0Q130	50~70	6520	88.00	0.0533
N0Q170	50~70	8025	72.93	0.0585

4.5 Mean Velocity Profile of Plumes

The mean velocity and width along the axis of a vertical plume are presented in this section. The velocities of a buoyant jet depend on the initial efflux velocity, density difference, as well as elevation. The mean concentration decay along the centreline can be described as:

$$\frac{\sqrt{M_0}}{z w_c} = \frac{1}{k_{pw}} \left(\frac{z}{L_m} \right)^{-2/3} \tag{4.67}$$

Substituting the expression of L_m in the formula yields:

$$\overline{w_c} = k_{pw} B_0^{1/3} z^{-1/3} \quad (4.68)$$

The centreline velocity is inversely proportional to the elevation to the power of one third. Another expression of the mean centreline velocity decay is:

$$\frac{\overline{w_c}}{w_0} = k_{pw} \left(\frac{\pi}{4} \right)^{1/3} Fr_0^{-1/3} \left(\frac{z}{D_0} \right)^{-1/3} \quad (4.69)$$

Taking the logarithm of both sides of Equation 4.65, the equation becomes:

$$\log \left(\frac{\sqrt{M_0}}{z \overline{w_c}} \right) = \log \left(\frac{1}{k_{pw}} \right) - \frac{2}{3} \log \left(\frac{z}{L_m} \right) \quad (4.70)$$

Figure 4.8 shows the mean centreline value obtained in the experiments. The experimental conditions are summarized in Table 4.5.

The linear fit of the experimental data will arrive at the following equation:

$$\log \left(\frac{\sqrt{M_0}}{z \overline{w_c}} \right) = -0.5853 - 0.6918 \log \left(\frac{z}{L_m} \right) \quad (4.71)$$

The value k_{pw} is equal to 3.85 from the above equation, which is same as that obtained by Panpanicolaou and List (1988). The range of decay constant, k_{pw} for buoyant jet varies from 3.4 to 4.7.

Table 4.5 Test conditions and comparison of velocity width of plumes

	w_0 (m/s)	ρ_a (g/cm ³)	ρ_0 (g/cm ³)	c_0 (μg/l)	Range (D_0)	k_{pwg}
D1Q080	0.568	1.054	0.963	879	48~70	182.1
D1Q160	0.993	1.054	0.963	879	53~67	179.2
D2Q080	0.531	1.077	0.947	936	48~70	149.8
D2Q150	0.916	1.077	0.947	936	53~70	229.6
D3Q080	0.540	1.093	0.915	797	48~70	155.5
N5Q075	0.427	1.110	0.844	1000	48~70	113.2
N5Q095	0.613	1.108	0.844	992	48~70	179.7
N5B090	0.553	1.108	0.844	394	11.7~32.9	127.4
BPLUME122901	0.500	1.055	0.997	88	0~42.9	116.9

Figure 4.8 Mean centreline axial velocities of ethanol- CaCl_2 plume

The results of Boussinesq plume behaviours were observed here although the initial density difference of the buoyant jet was well beyond the Boussinesq range. The minimum initial density difference was 4%, while the maximum was 24%.

The velocity width from the plume experiments is shown in *Figures 4.9 and 4.10*. The data are also found to be slightly greater than the results by Wang (2000). The test conditions are described in *Table 4.5*.

Linear curve fit was used to formulate the velocity width:

$$\frac{b_v}{D_0} = \frac{1}{\sqrt{k_{pwg}}} \frac{z - z_0}{D_0} \tag{4.72}$$

The values of k_{pwg} are tabulated in *Table 4.5*. As shown on *Figures 4.9 and 4.10*, the width results from the experiment were similar to those obtained by Wang (2000). The values of k_{pwg} are ranged from 113.2 to 229.6.

Figure 4.9 Velocity width for plumes from 0 to 45 D_0

Figure 4.10 Velocity widths for plumes from 50Do to 70Do

4.6 Mean Concentration Profiles of Plumes

The mean concentration of the plume and the concentration widths along the axis of a vertical plume are discussed in this section. The concentration profiles of the plumes were directly related to the density difference. *Figure 4.11* shows a typical PLIF image. The light intensity of dye was lower than that generated in a water jet. This is mainly due to the strong attenuation of the laser light in the calcium chloride solution.

The mean concentration decay along the plume centreline can be described as (e.g. Fischer et al. (1979), Hossain and Rodi (1982), Wood et al. (1993), etc.):

$$\frac{c_0 Q_0}{z c_c \sqrt{M_0}} = \frac{1}{k_{pc}} \left(\frac{z}{L_m} \right)^{2/3} \quad (4.73)$$

Similarly, the centreline concentration of plume in non-Boussinesq range is assumed to have the form:

$$\log\left(\frac{c_0 Q_0}{z c_c \sqrt{M_0}}\right) = \log\left(\frac{1}{k_{pc}}\right) + \lambda \log\left(\frac{z}{L_m}\right) \quad (4.74)$$

The concentration results were scattered around, since the actual concentration of every point is difficult to estimate. The centreline concentration results are shown in *Figure 4.12* in two different formats. *Figure 4.12.a* shows the centreline concentration decay in normal scale. The slopes of the curves become steeper as the flow move toward downstream. The centreline concentration decrease faster as the density difference becomes lesser.

However, the normal trends were not observed when the results were drawn on log-scale. (*Figure 4.12.b*) The data are scattered around. One of the major sources of the errors may come from the unknown mixing behaviour between the CaCl_2 and Ethanol solution. It was observed that, the mixing of the two fluids would generate heat. The rising in temperature might have affected the accuracy of PLIF measurements. On the other hand, the mixing of the two fluids may not be linear as assumed in the experiments.

Figure 4.11 Picture of PLIF measurement of plumes (D3Q080)

a) Mean centreline concentration decay in normal scale

b) Mean centreline concentration in log scale

Figure 4.12 Mean centreline concentration

Figure 4.13 shows the concentration width from the experiments. The width is no longer proportional to the elevation due to the effect of high density. However, most of the data is close to the value obtained by Law and Wang (2000). The widths of the concentration profile were correlative well with the initial velocity and density difference. The higher the density difference, the higher the curvature of the width edge will be. Also the higher the velocity, the higher the absolute value of width will be.

a) z/D_0 from 50 to 75

Figure 4.13 Concentration widths of plumes

b) z/D_0 from 0 to 75

Figure 4.13 Concentration widths of plumes (cont.)

4.7 Discussion on the Entrainment coefficient of Plumes

The entrainment coefficient of plumes can be derived from the data. The main assumption here is to assume a linear mixing behaviour between the ethanol and calcium chloride solutions. If $(1-\lambda)$ volume fraction of the source solution mixes with λ volume fraction of ambient, the concentration shall be:

$$\bar{c}(r, z) = \frac{c_0(1-\lambda)V + c_a\lambda V}{V} = c_0(1-\lambda) + c_a\lambda \quad (4.75)$$

where c_0 is the concentration of the source solution (ethanol), mass per volume, and c_a is the concentration of the ambient solution (calcium chloride), mass per volume.

Therefore, knowing the concentration, the volume fraction can be expressed as:

$$\lambda = \frac{\bar{c}(r, z) - c_0}{(c_a - c_0)} \quad (4.76)$$

The density of the plume is similarly expressed as:

$$\bar{\rho}(r, z) = \frac{\rho_0(1 - \lambda)V + \rho_a \lambda V}{V} \quad (4.77)$$

or

$$\bar{\rho}(r, z) = \rho_0 + \frac{\bar{c}(r, z) - c_0}{(c_a - c_0)} (\rho_a - \rho_0) \quad (4.78)$$

where ρ_0 is the density of source solution (ethanol) and ρ_a is the density of ambient solution (calcium chloride). The density of the solution refers to the mass of the solution in a unit volume.

The flow rate can be calculated from the following integration:

$$\bar{Q} = \int_0^\infty \bar{w}(r, z) \bar{\rho}(r, z) \cdot 2\pi r dr \quad (4.79)$$

Therefore,

$$\begin{aligned} \bar{Q}(z) &= \int_0^\infty \bar{w}(r, z) \left(\rho_a + \frac{\bar{c}(r, z) - c_0}{c_0} (\rho_0 - \rho_a) \right) \cdot 2\pi r dr \\ &= \int_0^\infty \bar{w}(r, z) \rho_a \cdot 2\pi r dr + \int_0^\infty \bar{w}(r, z) \frac{\bar{c}(r, z) - c_0}{c_0} (\rho_0 - \rho_a) \cdot 2\pi r dr \\ &= \int_0^\infty \bar{w}_c e^{-k_{jwg} \left(\frac{r}{z}\right)^2} \rho_a \cdot 2\pi r dr + \int_0^\infty \bar{w}_c e^{-k_{jwg} \left(\frac{r}{z}\right)^2} \frac{\bar{c}_c e^{-k_{jcg} \left(\frac{r}{z}\right)^2}}{c_0} (\rho_0 - \rho_a) \cdot 2\pi r dr \\ &= \bar{w}_c \rho_a 2\pi \frac{z^2}{-2k_{jwg}} e^{-k_{jwg} \left(\frac{r}{z}\right)^2} \Big|_0^\infty + \bar{w}_c \frac{\bar{c}_c}{c_0} (\rho_0 - \rho_a) 2\pi \frac{z^2}{2(-k_{jwg} - k_{jcg})} e^{\frac{(-k_{jwg} - k_{jcg}) r^2}{z^2}} \Big|_0^\infty \end{aligned} \quad (4.80)$$

The final form becomes:

$$\bar{Q}(z) = \pi \rho_a \bar{w}_c \frac{z^2}{k_{jwg}} - \frac{\pi \bar{w}_c \Delta \bar{c}_c (\rho_a - \rho_0)}{\Delta c_0 (k_{jwg} + k_{jcg})} z^2 \quad (4.81)$$

The second term takes into account the effect of density difference to the flow rate of plume. However, this term is very small because the maximum density difference was about 24%.

The flow rates in every plume experiments were calculated and second order polynomial functions were used to fit the data. *Figure 4.14* shows the results of the flow rate.

a) z/D_0 from 0 to 45

b) z/D_0 from 50 to 70

Figure 4.14 Flow rates of plumes

The coefficients of the best-fit second-order polynomial were used to obtain the derivative of the flow rate near the nozzle. The entrainment coefficient was then calculated based on Equation (4.66). *Table 4.6* shows the results of the entrainment coefficient near the nozzle. The results show that, the higher the density difference, the higher the entrainment coefficient will be. The entrainment coefficient near the nozzle was very high, from around 0.437 ~10. These were very different from the case of water jet, which has an entrainment coefficient of around 0.05. The variation of the plume entrainment might be due to the high density difference. However, the relationships between entrainment velocity and the plume velocity, density difference were still uncertain.

Table 4.6 Calculation of entrainment coefficient

Experiment	ρ_a	ρ_0	w_0 (m/s)	$\log(\rho_0/\rho_a)$	$\log(u_e/w_0)$	u_e/w_0
D1Q080	1.054	0.963	0.568	-0.039	0.876	7.516
D1Q160	1.054	0.963	0.993	-0.039	0.604	4.018
D2Q080	1.077	0.947	0.531	-0.056	0.842	6.950
D2Q150	1.077	0.947	0.916	-0.056	0.688	4.875
D3Q080	1.093	0.915	0.540	-0.077	0.931	8.531
N5Q075	1.110	0.844	0.427	-0.119	0.859	7.228
N5Q095	1.108	0.844	0.613	-0.118	1.006	10.139
N5B090	1.108	0.841	0.553	-0.120	0.674	4.720
BPLUME122901	1.055	0.997	0.500	-0.024	-0.359	0.437

4.8 Discussion on the Mass Flow Rate of Plumes

According to Equation (4.31), the mass flow rate q was modified by the ratio of the plume and ambient densities to the power of 2γ to yield the mass flow rate for the non-Boussinesq case. The value of 4.13, 0.105, 11.3 and 0.109 were used for coefficients, k_{pw} ,

η_{pwg} , k_{pc} and η_{pcg} , respectively. The value of negative $\frac{1}{2}$ was used for the coefficient γ . The predicted and actual flow rate for plume BPLUME122901 is compared in Figure 4.15. The predicted flow rate was very close to the actual flow rate.

Figure 4.15 Mass flow rates for plumes (Experiment BPlume122901)

The values were substituted into Equation (4.32) and the results were compared with the experimental flow rates in Figure 4.16. The predicted results were quite close to the actual measured values.

Figure 4.16 Predicted mass flow rate versus measured mass flow rate

4.9 Fire Plume Model

One of the major applications of non-Boussinesq plume equations is to predict the mass flux of a fire plume. The mass flux formula, Equations (4.31) and (4.32) can be converted into a fire plume model and inserted into a zone model for fire prediction.

Rooney and Linden (1997) suggested that the buoyancy flux in the non-Boussinesq case is related to the total (convective and radiative) power θ_t of the fire by:

$$B = \frac{\theta_t g}{\rho c_p T_a} \quad (4.82)$$

where T_a is the ambient temperature. Therefore, the initial buoyancy flux becomes:

$$B_0 = \frac{\theta_t g}{\rho_a c_p T_a} \quad (4.83)$$

The mass flow rate of a fire plume can then be obtained by substituting Equation (4.81) into (4.32):

$$\begin{aligned}
 q = & \pi k_{pw} \eta_{pwg}^2 \left(\frac{\theta_t g}{\rho_a c_p T_a} \right)^{1/3} (z - z_0)^{5/3} \rho_a \left(1 - \frac{k_{pc} \left(\frac{\theta_t g}{\rho_a c_p T_a} \right)^{2/3} (z - z_0)^{-5/3}}{g} \right)^{2\gamma} \\
 & - \pi k_{pw} \frac{\eta_{pcg}^2 \times \eta_{pwg}^2}{\eta_{pcg}^2 + \eta_{pwg}^2} \left(\frac{\theta_t g}{\rho_a c_p T_a} \right)^{1/3} (z - z_0)^{5/3} \\
 & \times \left(1 - \frac{k_{pc} \left(\frac{\theta_t g}{\rho_a c_p T_a} \right)^{2/3} (z - z_0)^{-5/3}}{g} \right)^{2\gamma} \left(\frac{k_{pc} \left(\frac{\theta_t g}{\rho_a c_p T_a} \right)^{2/3} (z - z_0)^{-5/3}}{g} \rho_a \right)
 \end{aligned} \quad (4.84)$$

or

$$\begin{aligned}
 q = & \pi k_{pw} \eta_{pwg}^2 \left(\frac{\theta_t g}{\rho_a c_p T_a} \right)^{1/3} (z - z_0)^{5/3} \rho_a \\
 & \times \left(1 - \frac{k_{pc} \left(\frac{\theta_t g}{\rho_a c_p T_a} \right)^{2/3} (z - z_0)^{-5/3}}{g} \right)^{2\gamma} \left(1 - \frac{\eta_{pcg}^2 \eta_{pwg}^2}{\eta_{pcg}^2 + \eta_{pwg}^2} \left(\frac{k_{pc} \left(\frac{\theta_t g}{\rho_a c_p T_a} \right)^{2/3} (z - z_0)^{-5/3}}{g} \rho_a \right) \right)
 \end{aligned} \quad (4.85)$$

The above model is compared with the well known formula provided by Heskestad (1984) and McCaffrey (1979). The results are shown in *Figure 4.17*. The rate of heat release for comparison is assumed to be 500kW. The mass flux of McCaffrey model is the largest compared to Heskestad and the present model. That is mainly because the McCaffrey model was derived based on near field plume experiments.

Figure 4.17 Comparison of mass flux of a 500 kW fire plume

Further away from the nozzle, the predictions of the present model follow a similar trend as the Heskestad model. Experimental data are required in the future for a more detailed comparison.

4.10 Conclusions

For jets, the mean centreline velocity decay constant k_{jw} , and the velocity width constant k_{jwg} were measured to be 6.369 and 80.4, respectively. The jet momentums were measured to be around 80% to 120% of the initial momentum. The results were considered reasonable and the maximum error was $\pm 20\%$.

The mean centreline concentration decay constant k_{jc} was from 3.584 to 5.094. The concentration width constant k_{jcg} varied from 41.785 to 60.467. The mass fluxes of dye were found to vary from 0.700 to 0.917 of the initial mass flux. The entrainment coefficient α was around 0.0562 to 0.0585.

For plumes, the mean centreline velocity decay constant k_{pw} , was measured to be 3.85, which was comparable to that obtained by other researchers. The velocity widths were wider than that measured by Law and Wang (2000) especially near the nozzle. The slope as well as the magnitude became similar to the case of Boussinesq plume further away from the nozzle. The velocity width constant varied from 113.2 to 229.6.

The initial entrainment coefficients at the nozzle were calculated from the extrapolated mass flux curve. The results show that, the higher the density difference, the higher the entrainment coefficient will be. The entrainment coefficient near the nozzle was very high, from around 0.437 ~10.

To incorporate the non-Boussinesq effects, the mass flow rate formula by Rooney and Linden (1997) is modified. The power of the density ratio, γ , is equal to negative $\frac{1}{2}$. The mass flux formula is given by:

$$q = \pi k_{pw} \eta_{pwg}^2 B_0^{1/3} (z - z_0)^{5/3} \rho_a \left(1 - \frac{k_{pc} B_0^{2/3} z^{-5/3}}{g} \right)^{2\gamma} - \pi k_{pw} \frac{\eta_{pcg}^2 \times \eta_{pwg}^2}{\eta_{pcg}^2 + \eta_{pwg}^2} B_0^{1/3} (z - z_0)^{5/3} \left(1 - \frac{k_{pc} B_0^{2/3} z^{-5/3}}{g} \right)^{2\gamma} \left(\frac{k_{pc} B_0^{2/3} z^{-5/3}}{g} \rho_a \right) \quad (4.86)$$

or

$$q = \pi k_{pw} B_0^{1/3} (z - z_0)^{5/3} \rho_a \left(1 - \frac{k_{pc} B_0^{2/3} z^{-5/3}}{g} \right)^{2\gamma} \left(\eta_{pwg}^2 - \frac{\eta_{pcg}^2 \times \eta_{pwg}^2}{\eta_{pcg}^2 + \eta_{pwg}^2} \left(\frac{k_{pc} B_0^{2/3} z^{-5/3}}{g} \right) \right) \quad (4.87)$$

where the value of k_{pw} , η_{pwg} , k_{pc} and η_{pcg} are 4.13, 0.105, 11.3 and 0.109, respectively (Law and Wang 2000).

Finally, based on the above results, a fire plume model that takes into consideration of the density difference is proposed as follows:

$$\begin{aligned} q &= \pi k_{pw} \eta_{pwg}^2 \left(\frac{\theta_i g}{\rho_a c_p T_a} \right)^{1/3} (z - z_0)^{5/3} \rho_a \\ &\times \left(1 - \frac{k_{pc} \left(\frac{\theta_i g}{\rho_a c_p T_a} \right)^{2/3} (z - z_0)^{-5/3}}{g} \right)^{2\gamma} \left(1 - \frac{\eta_{pcg}^2 \eta_{pwg}^2}{\eta_{pcg}^2 + \eta_{pwg}^2} \left(\frac{k_{pc} \left(\frac{\theta_i g}{\rho_a c_p T_a} \right)^{2/3} (z - z_0)^{-5/3}}{g} \rho_a \right) \right) \end{aligned} \tag{4.88}$$

CHAPTER 5

MULTI-COMPARTMENT FIRE TEST

5.1 Introduction

This chapter presents an exploratory study on compartment fire tests. The objectives are to understand the instrumentation for compartment fire tests and fire modelling using CFAST (zone model) and FDS (computational fluid dynamics model).

Analytical models for predicting fires have been evolving since the 1960s (Peacock et al. 1998). The number of fire models has increased by leaps and bounds. Many software programs have been developed for fire analysis, such as CFAST (Jones et al. 2000), Ozone (Cadorin 1999), ASET (Cooper & Stroup 1985), Jasmine (Cox G. & Kumars), and FDS (McGrattan, K. 2004).

Each fire will be different, because the fire development is affected by the ambient conditions. The development of fire can be separated into four typical stages, the initial stage, the development stage till the point of flashover, the fully developed stage, and the decay stage of the fire. From the temperature point of view, a fire will slowly build up the gas temperature in the room of origin after ignition. At the point of flashover, the radiation inside the fire room is so intense that every object in the room will be ignited. The entire compartment will be engulfed in fire. Some videos on the phenomenon of flashover in compartment fires show that prior to flashover, every object in the room is pyrolyzed and lots of vapours are generated. The gases are suddenly ignited. Flame encroaches on those objects far away from the origin of fire and the whole room starts burning. When the furniture in a room is burnt out, the fire will eventually decay and extinguish.

CFAST stands for Consolidated Model of Fire Growth and Smoke Transport. It was chosen for this research because of the following reasons. Many of the physical phenomena involved in fire are taken into account in this model, such as smoke flow due to pressure differences, and heat transfer including radiation, convection and conduction. The physical models are sound and valid with many supporting documents (Jones et al. 2000). It is able to model the consequences of fires, which have multi-compartment interactions, vertical and horizontal openings, nature and force ventilation, original and secondary fire sources, and even sprinkler effect. Some of the actual fire reports and tests have been successfully reconstructed by using CFAST.

FDS2 is the second released version of Fire Dynamic Simulator from NIST. It is a computational fluid dynamic model of fire-driven fluid flow. It solves numerically a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow with an emphasis on the smoke and heat transport from fires. (McGrattan et al., 2001) The source code is also available at no cost. Therefore, it was used in this study to provide a more detailed comparison of test data and simulation results.

5.2 Literature Review on Fire Modelling

For fire simulation, the rate of heat release (*HRR*) is one of the most important parameters (Babrauskas 1992). Most of the fire simulation software requires the user to input *HRR* as one of the parameters. Therefore, one must know the *HRR* of fire before he/she can use the software to calculate the fire behaviours.

However, heat release rate is not a characteristic property of a single or a group of fuel objects. The thermal boundary conditions will have significant effect on *HRR*. For example, the presence of the wall, ceiling or smoke layer will enhance the radiation feed back to the fuel surface. The pyrolysis rate or the mass loss rate of the fuel will be increased. Hence, there will be an increase on the heat release rate. On the other hand, the presence of thermal boundary will limit the supply of oxygen. The effect of ventilation

will come in when the fire arrives at its ventilation-control stage. This takes place for post-flashover fires. When the wind and turbulent effects come in, the fire situation will become even more complex.

Due to the importance of the *HRR*, it is worth while to understand how the actual measurement is conducted. There are four methods for obtaining the heat release rate. (Janssens, SFPE handbook) (1) Substitution method: The object for study will be burnt in a combustion chamber. The energy flowing in and out of the combustion chamber is carefully measured. Therefore, the energy released will be equal to the net energy gained in the outflow stream. The Ohio State University apparatus is built by making use of this principle. (2) Substitution method: Two runs for each specimen are required. In the first run, the specimen is burned in a combustion cell and the temperature in the exhaust stack is recorded. In the second run, the specimen is replaced by a non-combustible blanket and a gas burner is inserted for burning. The flow rate of the gas burner will be adjusted so that the temperature of the combustion product follows closely the first run. The rate of heat release for the specimen will correspond to the power of the gas flow in the second test. Apparatus using this method includes the FM construction materials calorimeter, and the FPL calorimeter. (3) Compensation method: In this method, a compensation gas burner is inserted in the combustion chamber and ignited before the specimen is ignited. When the specimen starts burning, the gas burner is adjusted so that the temperature of the exhaust gas is maintained. The reduction on the flow rate of the gas burner will correspond to the energy release of the specimen. The NBS-I calorimeter, and SRI calorimeter are constructed with the compensation method. (4) Oxygen consumption method. This is by far the most advanced technique for heat release measurement. In 1917 Thornton showed that, for most of the normal combustible material, a more or less constant net amount of heat is released per unit mass of oxygen consumed. The average of this value is 13.1kJ/g of oxygen. This method is implemented into the cone calorimeter and is used in many countries now.

Most of the solid fuels have complex fire behaviour. The *HRR* of gas, liquid and some plastic pool can be easily established. The burnings of most liquid fuels are stable

and have been studied most comprehensively. The mass loss rate of pool fires burning in open condition is strongly dependant on the surface area of pool. (Babrauskas, 1995)

$$\dot{m}'' = \dot{m}_{\infty}'' (1 - e^{-k\beta D}) \quad (5.1)$$

in which,

$\dot{m}''$	Mass loss rate per unit area	kg/m ²
$\dot{m}_{\infty}''$	Mass loss rate per unit area for an infinite-diameter pool	kg/m ²
$k\beta$	Product of the extinction-absorption coefficient of the flame (k) and the mean-beam-length corrector (β)	m ⁻¹
D	Pool diameter	m

Crib fire burning rate has also been studied since a long time ago. Many research works on crib fires have been conducted with some available formulas, yet they are unable to cover all the complex situations, such as ignition method, and presence of thermal boundary conditions. Babrauskas (1995) provided a set of formulas for estimation of crib burning based on the works of Nilsson, Yamashika and Kurimoto. The mass loss rate for crib fire ignited instantaneously is based on three factors, the surface pyrolysis rate, spacing of cribs and the room ventilation. The smallest value predicted by the following formulas gives an approximate value of *HRR*.

Fuel-surface control:

$$\dot{m} = \frac{4}{D} m_0 v_p \left(1 - \frac{2v_p t}{D}\right) \quad (5.2)$$

or

$$\dot{m} = \frac{4}{D} m_0 v_p \left(\frac{m}{m_0}\right)^{0.5} \quad (5.3)$$

with

$$m = m_0 - \sum_i \dot{m}_i(t_i) \Delta t$$

Crib-porosity control:

$$\dot{m} = 4.4 \times 10^{-4} \left(\frac{S}{h_c} \right) \left(\frac{m}{D} \right) \quad (5.4)$$

Room-ventilation control

$$\dot{m} = 0.12 A_v \sqrt{h_v} \quad (5.5)$$

in which, D is the stick thickness, m_0 is the initial mass of crib, t is time since ignition, h_c is crib height, S is the spacing between sticks, opening area A_v and height h_v (Figure 5.1). The surface regression velocity v_p for wood is $2.2 \times 10^{-6} D^{-0.6}$.

Here is an example of using the Equation (5.2) –(5.5). Assume a block of wooden crib of six layers is burned in a room. The room has an opening of $0.8 \times 2.0\text{m}$. The cross sections of the wooden sticks are $0.04 \times 0.04\text{m}$ and the spacing between sticks is 0.075m . Lengths of wooden sticks are 0.5m . The properties of wood can be taken as follows:

$$\rho = 500\text{kg/m}^3$$

$$c = 2.8\text{kJ/kg}^\circ\text{C}$$

$$k = 0.122\text{W/m}^\circ\text{C}.$$

Figure 5.1 Construction of Wooden cribs

Figure 5.2 Mass Loss Rate of Wooden Crib

The initial mass of the wooden crib is 12 kg. Ventilation factor is calculated as $2.263 \text{ m}^{2.5}$. If the ventilation controls the fire, the mass loss rate will be 0.272 kg/s , which

is much higher than the other values. Therefore, it is impossible for the fire to proceed to ventilation-control stage. *Figure 5.2* shows the different mass loss rates calculated from the Equation (5.2) to (5.4) and the lowest curve at any time is assumed to be the actual mass loss rate.

The difference between Equation (5.2) and (5.3) is not significant. In the first 11 minutes of burning, fuel surface controls the mass loss rate. When the mass of the fuel is slowly consumed, the porosity of the crib controls the burning rate.

However, in practice, many of the situations cannot be easily estimated, including the method of ignition, the arrangement of sticks, the overall shape of cribs, and also the location of crib in a room with regard to the ventilation opening. The behaviour of burning furniture will be the most complicated case to predict. NIST has conducted many experiments on upholstered furniture in both bench-scale and full-scale tests. Babrauskas (1984, 1986, and 1995) also provided some empirical rules for estimating the *HRR* for actual fire from the bench-scale data.

For a design situation, no one knows what the room content will be. The heat release rate follows the t-square method. The assumption here is that the fire growth will be proportional to the square of time. (Karlsson, and Quintiere, 2000)

$$HRR = \alpha t^2 \quad (5.6)$$

The coefficient α here will have different values according to slow, medium, fast and ultra-fast growth fire. After the *HRR* reaches its maximum value, it will be constant. The growth rate and the maximum value will depend on the building type and function, from some statistical data. (Kersken-Bradley, n.d.)

If the room contents are known, like some of the situations in fire investigation and reconstruction, a more accurate *HRR* curve can be predicted from some bench scale experiments. NIST is now maintaining a fire database for heat release rate of furniture

combustion. The data of their tests can be directly downloaded from the internet for modelling usage. Therefore, in this case, either a full-scale fire test can be conducted or data from bench scale tests can be used for the *HRR* curve.

Mowrer and Williamson (1990) presented a general method of estimating heat release rate. Exponential growth fire and t-square method were discussed in detail in this paper. A method of characterizing the actual test data was also presented.

Fire experiments are necessary to study the complex behaviour of building fires. Among those enclosure fire experiments, two categories of fire tests can be identified. In the first category, single phenomenon is isolated for study. The tests are normally conducted in a regular and well defined space. In many cases, the entire testing facilities are under an indoor structure. This can eliminate the possible impact of unknown thermal boundary conditions such as wind, temperature and weather variations.

Steckler et al. (1986) conducted a series of full-scale experiments, to find out the mass flow rate induced by fire through doorway. The tests were conducted in a two-room compartment. A propane diffuse burner was used as a fire source. An array of bidirectional pressure probes and thermocouples were employed to measure the gas temperature and flow velocities. They found out that the average value of orifice coefficient, C_d , is 0.68. The mass flow rate through doorway, $\dot{m}_a$, was proportional to the ventilation parameter $A_v H_v^{1/2}$, where A_v is the area and H_v is the height of the opening.

In order to identify the near field entrainment of the fire plume in compartment, Dembsey and his colleagues (1995) conducted a series of 20 full scale experiments. The tests were carried out in a standard size, single fire room. The fire sources are four rectangular propane porous surface burners. Six sets of temperature profiles were measured. They are the ceiling jet temperature, doorway centreline temperature, floor surface temperature, front corner temperature, interior wall surface temperature at the front corner and the corresponding exterior wall surface temperature. The flow rate of propane was adjusted for each test to produce different fire sizes. The heat release rates

ranged from 330 to 980 kW. The entrainment rates were compared to different plume models, and the results showed that the model by Baum and McCaffrey were most suitable for prediction. Three sets of results in these experiments were also compared with zone modelling software, CFAST and FIRST (Dembsey et al 1995). They found that the CFAST and FIRST will normally over-predict the upper-layer gas temperature by 40°C.

Peacock et al (1993) described the results of several experiments in his paper to make comparison with the zone model program CFAST. Five different scenarios were provided: (1) A single-room test burning with upholstered furniture; (2) Single-room test burning with furniture and wall surface; (3) Three-room test with gas burner as fire source; (4) Multi-room test, in a room-corridor configuration, using gas burner; (5) Multi-room fire test in a seven-storey building, with and without stairwell pressurization. The results were compared in five aspects, namely, the layer temperature and interface position, the gas species, heat release and pyrolysis rate, pressure, and gas flow. The differences between the CFAST predictions and the actual results vary from a few percent to a factor of two to three times over. Several limitations of the model were also pointed out for future research work.

There are quite a number of tests conducted on reconstruction of fire scenarios. Woolley et al. (1983) conducted an ignition fire tests on beds and bedding when investigating the Warlingham Park Hospital Fire occurred in 1981. The tests involved ignition studies with matches and cigarettes, studies of fire growth in beds with adjacent wooden lockers. Temperature, radiation, smoke and toxic gases were measured.

Friedman (1992) conducted a survey on the existing computer models for fire and smoke around the world. In 1989, 36 fire computer models were identified. The number increased to 62 in 1991. Recently, altogether 74 computer models are available. (Friedman, 2002) These models are separated into six categories for different purposes and techniques. Among them, 52 are classified as zone models, and twenty are CFD models. Others are for detector response, egress simulation, fire endurance, and

miscellaneous purposes. Some of the well known models will be introduced in this section.

CFAST is one of the most comprehensive multi-compartment zone-modelling software in the world. It is developed and maintained by NIST. (Peacock et al., 2000) Supporting documents are available from many sources. Heat release rate needs to be input by either user specified, from database of objects, or t-square method. The fire source is modelled as a point or a surface giving out energy and gas species according to the given heat release rate. McCaffrey's plume model is chosen for flame and fire plume simulation. The flow of the smoke is driven by pressure difference derived from temperature variation. The model is able to solve for the smoke layer position, gas temperature, pressure and flow rate, wall surface temperature and heat transfer, as well as the gas species concentration. However, no pyrolysis model is implemented in the software to predict fire growth.

FDS2 is a computational fluid dynamic program specially designed for fire modelling. In the model, an approximate form of Navier-Stokes equation is used. The computation can be either treated as Direct Numerical Simulation (DNS), in which the dissipative terms are computed directly, or as Large Eddy Simulation (LES), in which the large-scale eddies are computed directly and the sub-grid scale dissipative processes are modelled. The boundary of simulation is input by rectangular blocks. Fire source can be specified as heat source according to a particular *HRR* curve or a block of material with known fire behaviours. A comprehensive and detailed result can be produced. However, computational time varies from a few hours to a few days, depending on the size of calculation.

A summary of above mentioned computer codes is given in *Table 5.1*.

Table 5.1 Summary of Computer Models for Fire and Smoke Simulation

Model	Classification	Capabilities	Limitation
CFAST	2-zone model	It is able to predict pre- and post-flashover fire of multi-compartment. Temperature of gas and wall surface, gases concentration, flow, pressure and radiation will be provided.	No pyrolysis model is included in the software.
Ozone	2-zone and 1-zone	It is able to predict pre- and post-flashover fire of single compartment. Gas temperature curve will be provided. Statistic data is implemented in the software.	Gases concentrations are not calculated.
ASET	2-zone	It is able to simulate the smoke layer thickness, temperature, concentrations of gases in a single compartment fire.	It cannot predict post-flashover fire.
COMPF2	1-zone	It is able to predict post-flashover fire in a single compartment.	It is only suitable for post-flashover fire.

FDS2	CFD	It is able to predict most of the fire situation. Complex geometries can be model.	The input of geometry is tedious and time consuming. It requires expensive computer resources to run. It is not able to model curved boundaries.

5.3 Setup of the Multi-Compartment Fire Test

The Housing Development Board in Singapore is trying out a new concept, “White-Block”, where there is no rigid partition within the space. The buyers can have the flexibility to decide on the internal layout of their houses. However, different conditions will be expected in this kind of new flats in case of fire scenarios. Rooms will no longer be used to compartmentalize fire. Larger space area and bigger opening will allow the smoke and hot gas to move faster. The compartment fire tests were conducted jointly with Singapore Civil Defence Force (SCDF), and Housing Development Board (HDB). They provided a good means for the author to try out instrumented fire tests, fire simulation using CFAST & FDS, and fire simulation using in-house software incorporating the entrainment model of plume. However due to time constraint, the last objective could not be fulfilled.

A set of fire experiments was conducted for simple comparison of smoke and fire movement in white-block and normal flat. The fire tests for white-block and normal flat fire tests were called CF001 and CF002 accordingly. The objectives of these experiments were in two parts. The first objective was to compare the differences of fire and smoke behaviours between the white-block and the normal configuration of HDB flats. The second was to use computing software to simulate the fire conditions in a compartment.

Two compartments in an empty building were modified to represent the different housing concepts. Temperature and gas contents were measured at selected locations. A technical officer was employed to take the video of the fire tests. The results from experiments were compared with each other and the differences in computer simulation were pointed out.

The layouts and dimension of the two compartments are shown in *Figure 5.3*. Heights of the compartments were 2.65 m. Ceilings and Floors of the compartments were reinforced concrete slab with 100 mm thick. The partition walls comprised single-leaf brick walls. Wall thickness was either 100 or 200 mm as shown in *Figure 5.3*. There was only one concrete wall, which was at the far right in the drawing and only for white-block case. Columns shaded are in black in *Figure 5.3*. The soffits of the doors were 25cm depth from the ceiling, which might cause uncertainty in the experimental results.

a) Normal HDB Configuration

Figure 5.3 Layout and Dimension of the Compartment Fire Tests

b) White-Block Flat Configuration

Figure 5.3 Layout and Dimension of the Compartment Fire Tests (cont.)

The entire compartments were separated into five rooms, as shown in Figure 5.4. The sizes and locations of all the rooms were similar in both cases. The fuels for the fire tests were placed in Rm1. Rm1 is the room of fire origin, as shown in Figure 5.4. There were quite a number of doors and windows in this compartment. The letter **W** denotes the windows, while **Do** denotes the doorways. The sizes of windows and doors are shown in Table 5.2. The numbers in IDs of doors and windows represent the connected room, and **0** represents external atmosphere.

a) Normal Configuration

b) White-Block Configuration

Figure 5.4 Rooms and Opening and Their Identified Numbers

Table 5.2 Dimensions of Openings for Compartment Fire Tests

	Sill (m)	Soffit (m)	Height (m)	Width (m)
Doors	0	2.4	2.4	0.65
Windows	1.0	2.4	1.4	1.90

All the doors and window W1-0 were left open during the tests as glass will always break in case of fire. The rest of the windows W2-0 to W5-0 were all made of glass panels. Although they were closed for the tests, some smoke and hot gas leaked out through them.

The temperature of gases in a fire compartment is one of the most important parameters to be quantified. From literature review of thermometry, many of the measurement techniques are developed for temperature measurement, such as expansion and contraction of liquid or metal, changes of electrical resistance, and changes of electrical potential due to temperature. Thermocouple is by far the most commonly used device for fast and accurate temperature measurement. It is in a form of a circuit with two dissimilar conductors. From the knowledge of thermoelectricity, if a temperature gradient is established in a conductor, the electrons will be driven to flow around the circuit. Hence an electric potential difference will be established, which is dependent on the type of material and temperature difference. Due to the difficulty in measuring this potential in an isolated conductor, two dissimilar conductors are needed. Therefore, thermocouple can measure temperature differences by comparing the differences in thermo electromotive force generated between two conductors.

K type thermocouples, which are made of nickel-chromium and nickel-aluminium, were employed in these experiments because of a wide range of measurements and acceptable accuracy. The length of thermocouples ranged from 10 to 14 m with 2 to 4 m mineral insulated head. The insulated parts of thermocouples were made of ceramic powder and stainless steel (SS316) with a sheath diameter of 1.6 mm. This provides a suitable temperature measurement of up to around 900°C. The standard tolerance for K

type thermocouple is $\pm 2.5^{\circ}\text{C}$ or ± 0.0075 of range, which is $\pm 6.8^{\circ}\text{C}$ for a range up to 900°C . Other than the head of thermocouple, the rest of the 8 to 10 m thermocouple wire was insulated by PVC and could sustain up to a maximum temperature of 105°C . Specification and series number of all the thermocouples are provided in Appendix A.

Two thermocouples, S/N: V02996 and S/N: V02997, together with the data logger used in the experiments, were sent to SPRING Singapore (original PSB Singapore) for calibration. For low range temperature, 0 to 200°C , calibration was conducted by comparison with Standard Platinum Resistance Thermometers in constant temperature baths. At higher temperature up to 900°C , a Type S thermocouple was used as a reference and calibration was performed in a horizontal tube furnace. The immersion length of the thermocouples for calibration was approximately 300mm.

The calibration followed the temperature scale defined by International Temperature Scale of 1990 (ITS90). Results showed that the uncertainty of temperature measurement was $\pm 1.5^{\circ}\text{C}$ over the temperature range of 0 to 900°C . This was considered acceptable and no adjustment was made for the recorded data due to instrumentation error.

To fix the thermocouples in the fire room, several steel trees were fabricated. The trees were made of two components, a base and a vertical bar. Both of them were made of mild steel. The vertical steel bars can be slotted into the base and be fixed with bolts. Five holes were drilled on the vertical steel bars, which allowed the thermocouple wire to pass through. However, the holes were redundant because thermocouples can be easily tied onto steel bar with normal steel wire. For trees that support five thermocouples, the vertical distances of the thermocouple above the ground are 2.55m, 2.05m, 1.55m, 1.05m and 0.55m. For trees that only support three thermocouples, the vertical distances are 2.55m, 2.05m, and 1.55m.

The fuels comprised wooden cribs, constructed by stacking wooden sticks in alternative direction. The wood was *Pinus Silvestris*, which is a kind of pine. The wooden

sticks were directly imported from Romania wrapped up in polythene sheets to avoid excessive accumulation of moisture. The conditions of the sticks were carefully controlled. The densities were maintained in the range of 400 to 600 kg/m³, while the moisture content was within 10 to 15 %. The cross sections of the sticks were square with 39 ± 2 mm in width.

A total of 90 kg wooden crib was used for each test in the original plan, based on some modelling conducted using Jasmine. However, calibration of the weighing machine was conducted after the first test. Wooden crib with the same height as the first test was used in the second test. The total weights of wooden cribs for the tests on Normal and White-Block configuration were 114 kg and 104 kg, respectively. The difference was due to two reasons. Firstly, the long wooden sticks (1.3 m) were insufficient and they were replaced by combinations of three short wooden sticks (0.5 m) for the second last layer in the normal configuration test. That caused an increase in volume of wood by 1600cm³, around 0.8kg. Secondly, the accuracy of the weighing machine was ± 0.5 kg, and reading error may have occurred during the preparation. This was considered as the main error.

The construction of wooden cribs followed the 13A fire in Singapore Standard SS232 with some alterations. Twenty layers of sticks were placed instead of fourteen in the standard. Bricks and steel bars were used to support the cribs. No liquid tray was provided under the wooden cribs, unlike what is stated in the standard.

Wooden cribs were used in these experiments because of similar combustion behaviours between wood and real furniture, which was the prime concern of fire fighters. Besides, the burning of wooden crib is much more repeatable compared to used furniture. However, the heat release rate of solids, including crib fire, is always difficult to predict accurately.

Equations are available in literature for *HRR* of wooden crib fire. (Equation (5.2) to (5.5)) However, the arrangement of wooden sticks was different from actual test. Since no data is available to address the difference in configuration, a simple assumption was

made for the *HRR* estimation. Each of the wooden cribs for the actual tests had 20 layers. There were five pieces of 1.3 m long sticks in the longitudinal direction and 13 pieces of 0.5 m short sticks in the transverse direction. An imaginary wooden crib with five pieces of 0.44 m sticks on each layer was assumed to have similar mass lost behaviour as the actual wooden crib. They had the same height and spacing between adjacent sticks. The *HRR* histories per unit mass of the two wooden cribs were assumed to be the same. The following parameters in *Table 5.3* were assumed. The mass of actual wooden crib takes the average of two tests, which was 109 kg.

Table 5.3 Parameters for *HRR* Calculation of Wooden Crib

$\rho = 500\text{kg/m}^3$	$D = 0.04\text{m}$	$\Delta H_c = 20\text{MJ/kg}$	$c = 2.8\text{kJ/kg}^\circ\text{C}$
$S = 0.06\text{m}$	$v_p = 2.20 \times 10^{-6} \times D$	$k = 0.122\text{W/m}^\circ\text{C}$	$A_v \sqrt{H_v} = 4.624\text{m}^{3/2}$

A factor of 10.86 (109 kg / 10.04 kg) was multiplied to the rate of heat release in the single compartment fire test to get the *HRR* for compartment tests.

5.4 Results of Multi-Compartment Fire Test

The gas temperature was recorded at every 20 second interval during the two fire tests. The complete set of data is included in Appendix B. The normal HDB block and white-block fire tests were referred to as CF001 and CF002, respectively. The maximum temperature for CF001 was 740°C, registered by the top thermocouple on point 1 (*Figure 5.5.a*). The results of all of the thermocouple trees are also shown in *Figure 5.5*. Large temperature gaps appeared between elevation 1550 and 2050 mm for most of the measuring points.

Similarly, the temperature of the second fire test is shown in *Figure 5.6*.

CHAPTER 5

Figure 5.5 Temperature History of Each Thermocouple Tree in CF001 Test

i) Point 9

j) Plan View

Figure 5.5 Temperature History of Each Thermocouple Tree in CF001 Test (cont.)

It is of great interest to obtain the average temperature of the smoke layer in the compartment and also the range of differences. The elevation of smoke layer was difficult to be ascertained during experiments. Therefore, the temperatures of gases were used to indicate the smoke layer, which was similar to the hot gas layer. For both cases, the elevations of hot gas layers were more or less the same. Large differences in temperature were observed between the thermocouple at elevation 1550 and 2050mm. The smoke layer interface was calculated as mid-way between 1550 and 2050mm in Rm1, which was 1800mm from floor.

a) Point 1

b) Point 2

Figure 5.6 Temperature History of Each Thermocouple Tree in CF002 Test

c) Point 3

d) Point 4

e) Point 5

f) Point 6

g) Point 7

h) Point 8

i) Point 9

Figure 5.6 Temperature History of Each Thermocouple Tree in CF002 Test (cont.)

The average temperatures of upper layer at any time of a particular location were calculated based on the concept of equivalence of energy. The temperature was assumed to be constant around the particular thermocouple, as T_1 , T_2 and T_3 shown in *Figure 5.7*.

Figure 5.7 Definition of symbols

The internal energy estimated from the average temperature of the gas layer should be equal to the actual internal energy. The actual energy of a gas layer e is given by:

$$e = \int c_p \Delta T dm \quad (5.7)$$

The energy is also expressed in terms of average temperature:

$$e = c_p \Delta \bar{T} m \quad (5.8)$$

From the ideal gas law, the density of gas can be expressed as:

$$\rho = \frac{P_0 M}{R_0 T} \quad (5.9)$$

Equation (5.9) is substituted into (5.7) and (5.8) and they are equalled:

$$c_p A \int_{H_D}^{H_0} \Delta T \frac{PM}{R_0 T} dh = c_p A \Delta \bar{T} \frac{PM}{R_0 T} (H_0 - H_D) \quad (5.10)$$

From *Figure 5.7*, the smoke layer depth $(H_0 - H_D)$ becomes:

$$(H_0 - H_D) = l_1 + l_2 \quad (5.11)$$

Therefore,

$$\Delta \bar{T} = \frac{\left(\frac{\Delta T_1}{T} l_1 + \frac{\Delta T_2}{T} l_2 \right) \bar{T}}{(l_1 + l_2)} \tag{5.12}$$

in which,

R_0	Universal gas constant, $R_0 = 8.314 \text{ J/(mol K)}$	J/(mol K)
R	Gas constant for air, $R = R_0/M = 287 \text{ J/(kg K)}$	J/(kg K)
P_0	Pressure of atmosphere, $P_0 = 1.013 \times 10^5 \text{ N/m}^2$	N/m ²
c_p	Air specific heat at constant pressure, $c_p = 1000 \text{ kJ/kg K}$	kJ/kg K
M	Molecule weight	kg/mol
T_0	Ambient temperature $T_0 = 29^\circ\text{C} (302.15\text{K})$	°C
T_1, T_2	Temperature of thermocouples	°C
l_1, l_2	Height of gas layer refer to Figure 4.14, $l_1 = 0.35\text{m}, l_2 = 0.5\text{m}$	m

The same concept could be applied to the whole fire room, in which different areas were assigned to each thermocouple point according to *Table 5.4* and the equation is:

$$\Delta \bar{T} = \left(\frac{\sum A}{\sum \frac{A_i}{1 + T_a / \Delta T_i}} - 1 \right)^{-1} T_a \tag{5.13}$$

The resulting average temperatures for each thermocouple tree and the whole fire room are shown in *Figure 5.8 and 5.9*, respectively.

Table 5.4 Assumed Measurement Area of Thermocouple Trees and Dimension of the Room of Fire Origin Rm1

	T1	T2	T3	T4	T5	T6	Rm1
Width	2.5	0.7	2.2	2.2	1.0	1.0	3.2
Depth	1.4	1.4	1.6	0.9	1.5	1.0	3.9
Area	3.5	0.98	3.52	1.98	1.5	1.0	12.48

a) Test CF001

b) Test CF002

Figure 5.8 Average Measured Upper-Layer Temperature in Rm1

a) Test CF001

b) Test CF002

Figure 5.9 Average Measured Lower-Layer Temperature in Rm1

Most of the stages of fire development can be observed from the graphs, including ignition, fire development, fully developed fire, decay, and suppression. (Figure 5.9) The combustion of wooden crib for the first test was faster after ignition. Higher temperature resulted in the first test for normal compartment.

Table 5.5 shows the values deduced from the average temperature curves from Figure 5.9. The maximum average temperature for CF001 and CF002 tests were 432 and 400°C, accordingly. The temperature for normal configuration fire test was slightly higher than the white-block fire test. The temperature increase at the beginning was also faster than white-block case due to addition of accelerant.

Table 5.5 Comparison for The Two Experiments

	CF001	CF002
Temperature increasing rate of developing part	0.38°C/sec	0.26°C/sec
Time from ignition to fully developed stage	900sec	1560sec
Maximum average temperature	432°C	400°C
Suppression rate	-13°C/sec	-0.40°C/sec
Suppression time	20sec	437sec
Volume of Walter Used	600 liters	60 liters

Far away from the fire source, the temperature of gas would have significantly decreased. A series of contour of gas temperature at several instances of time are shown in Figure 5.11. The reference locations are shown in Figure 5.10. The temperatures along the boundary of the graphs were assumed to be the same as the closest thermocouple temperature.

a) Distances and Thermocouple Tree along the Path of 1-2-7-8-9

b) Plan View for CF001

c) Plan View for CF002

Figure 5.10 Smoke Outflow Path 1-2-7-8-9

a) CF001-0600sec

b) CF001-1100sec

Figure 5.11 Gas Temperature Contours

c) CF001-1500sec

d) CF001-1720sec

e) CF002-0700sec

f) CF002-1200sec

g) CF002-1700sec

h) CF002-2040sec

Figure 5.11 Gas Temperature Contours (cont.)

(Figure 5.11.a and e represent the temperature distribution for the initial stage of fire. Figure 5.11.b and f represent the developing stage, while Figure 5.11.c and g for most developed stage, and Figure 4.19.d and h for the suppression stage.)

The graphs in Figure 5.11 were drawn from selected instances of temperature results, which represent the initial, developing, fully developed and suppression stage. Therefore, straight lines were observed for all the curves near the boundary. For the fully

developed stage (*Figure 5.11.c and g*), the steepest temperature gradient occurred near the bottom of smoke layers and around 2m outside the fire room Rm1. Outside the fire room in the living halls, Rm2 and Rm3, the temperature was not very high. This agreed well with the observation during the tests.

These graphs show the gas temperature distribution of a particular instant of time on a vertical sheet. Unknown temperature on the boundary will be assumed to be the same as the nearest thermocouple temperature. *Figures 5.11.a to d* are for the first compartment fire tests. In the first 600-second, the temperature was not changing too much. At around 1100-second, high temperature was developed in the fire room. The steep temperature gradient, between 100°C and 50°C, roughly indicates the location of smoke-flesh air interface. The results for test CF002 were similar, as shown in *Figures 5.11.e to h*. The smoke layer formed in the stage of around 1200-second to 1700-second. The temperature was around 150°C before 5m and 100°C after 5m from the source of fire.

5.5 Uncertainties of Multi-Compartment Fire Test

The compartment fire test was conducted in a real HDB flat. The accuracies of the fire test depended on many factors, such as the conditions of the fuel, the movement of the air and the accuracies of the equipment. Therefore, we should discuss the accuracies of the results based on three major factors: the fuel, the ambient conditions, and the equipment.

The source of fire contained two parts, the wooden crib and gasoline. The gasoline was poured on the wooden crib before the fire started to make it easy for the wooden crib to start burning. The amount of gasoline was around 300ml but no precise measurement was done. This caused an uncontrolled *HRR* increase at the beginning. On the other hand, although the wooden sticks were quite uniform, there were differences in timing of the ignition of the wood surface. All these factors affected the *HRR* generated through the experiments.

The geometry of the compartment brought in the second part of uncertainties. The compartment contained quite a few rooms and many openings. At the same time, the outside wind velocity was difficult to estimate, which had significant effect on the air movement inside the compartment. Therefore, the movement of the smoke and in-coming fresh air was difficult to estimate. From the oxygen supply point of views, although the fire was quite big, there was enough oxygen for the fire to grow in the oxygen-rich condition.

The third uncertain factor came from the limitation of the equipment. The thermocouples registered the temperature due to the heat of surrounding air and radiation of all the objects in the compartment, the flame, the wall etc. The size of the thermocouples are relatively small, the delay of time is not an issue. However, it was difficult to calculate the gas temperature alone due to the radiation from the surrounding.

In a nutshell, the ignitions of fuel, the geometry of the compartments and the thermocouples contributed to the errors in the measurements. These factors mainly affected the *HRR*, the movement of air, and the temperature measurement.

CHAPTER 6

CALCULATION AND COMPUTER SIMULATIONS RESULTS

6.1 Introduction

In this chapter, the predictions by hand calculation and computer simulation were presented. The hand calculation method of MQH (refer to McCaffrey, Quintiere, and Harkleroad) was employed to demonstrate the effects of some important parameters. A zone model, CFAST, and a CFD model, FDS2, were used to reconstruct the fire tests. The upper-layer temperature in the fire room, temperature profiles along the longest smoke outflow path, and maximum ceiling jet temperature profiles were compared with the experimental results.

The chapter is separated into seven sections. First section is introduction. In the following three sections, the predictions of MQH method (Karlsson et al. 2000), CFAST, and FDS2 are shown individually. Section five shows the comparison of temperatures histories in the fire room and living room among the experimental results and the three models. The comparisons of ceiling jet maximum temperatures and slice temperatures profiles along line 1-2-7-8-9 are shown in section six and seven.

The full-scale compartment fire tests described in the previous chapter were controlled experiments. However, differences were observed in the comparison. This shows the difficulties in predicting a real fire scenario. On the other hand, this also shows that no software is perfect. Each of them will only be suitable for certain range of conditions. They may predict wrongly when used outside of their range.

6.2 Prediction of MQH Hand Calculation Method

A hand calculation method was presented by McCaffrey, Quintiere, and Harkleroad. (Karlsson and Quintiere, 2000) The method was derived for pre-flashover fire. A simple energy balance formula was used, that is, the rate of energy released in the compartment is equal to the sum of rate of energy lost due to fluid flow out through opening and rate of heat loss by the hot gas to compartment boundaries.

$$\theta = \dot{m}_g c_p (T_g - T_a) + h_k A_T (T_g - T_a) \quad (6.1)$$

in which,

$\dot{m}_g$	is mass outflow rate	kg/s
h_k	is heat conduction coefficient	kW/(m ² K)
θ	is <i>HRR</i>	kW
A_T	is boundary surface area for heat loss	m ²
c_p	is heat capacities of air	J/(kgK)
T_g	is the upper-layer temperature in compartment	°C
T_a	is the lower-layer temperature in compartment	°C

They derived a set of easily computed dimensionless variables and determined a number of constants through regression analysis. Finally, they arrived at a simple expression.

$$\frac{\Delta T}{T_a} = 1.63 \left(\frac{\theta}{\sqrt{g} \rho_a c_p T_a A_0 \sqrt{H_0}} \right)^{2/3} \left(\frac{h_k A_T}{\sqrt{g} \rho_a c_p T_a A_0 \sqrt{H_0}} \right)^{-1/3} \quad (6.2)$$

A more convenient form of the equation would be:

$$\Delta T = 6.85 \left(\frac{\theta^2}{A_0 \sqrt{H_0} h_k A_T} \right)^{1/3} \quad (6.3)$$

The effective heat conduction coefficient h_k depends on the material properties of the boundary and the time. The time at which the conduction can be considered to be

approaching stationary heat conduction is termed thermal penetration time, t_p . This time can be given as:

$$t_p = \frac{\delta^2}{4\alpha} \tag{6.4}$$

(Karlsson and Quintiere, 2000)

in which,

t_p	is thermal penetration time	sec
δ	is thickness of thermal boundary	m
α	is thermal diffusivity, $\alpha = k/\rho c$	m ² /s
k	is thermal conductivity	W/m°C
ρ	is density	kg/m ³
c	is specific heat	J/kg°C

The material of ceiling and floor was assumed to be normal weight concrete with 0.1m thickness in the fire tests. The walls were assumed to be clay brick with 0.1 m thick. The material properties were listed in *Table 6.1*.

Table 6.1 Material Properties for Compartment Fire Tests

	Material	Conductivity (W/m°C)	Specific Heat (J/kg°C)	Density (kg/m ³)
Ceiling	Normal Weight Concrete	1.75	1000	2200
Floor	Normal Weight Concrete	1.75	1000	2200
Wall	Clay Brick	1.50	960	2645

The thermal penetration times for the ceiling and floor were 3142 seconds, (52 minutes). The thermal penetration time for walls was 4232 seconds, more than an hour. However, the time for each of the test was around 30 minutes. Therefore, heat conduction through the thermal boundary was never stable during the tests.

For $t < t_p$ (6.5)
$$h_k = \sqrt{\frac{k\rho c}{t}}$$

or
$$h_k = \frac{A_w}{A_T} \sqrt{\frac{(k\rho c)_w}{t}} + \frac{A_C}{A_T} \sqrt{\frac{(k\rho c)_C}{t}} + \frac{A_F}{A_T} \sqrt{\frac{(k\rho c)_F}{t}}$$
 (6.6)

and for $t \geq t_p$ (6.7)
$$h_k = \frac{k}{\delta}$$

or
$$h_k = \frac{A_w}{A_T} \frac{k_w}{\delta_w} + \frac{A_C}{A_T} \frac{k_C}{\delta_C} + \frac{A_F}{A_T} \frac{k_F}{\delta_F}$$
 (6.8)

in which,

t_p	is thermal penetration time	sec
δ	is thickness of thermal boundary	m
k	is thermal conductivity	W/m°C
ρ	is density	kg/m ³
c	is specific heat	J/kg°C
w, C, F	are walls, ceilings, and floor	

The calculation of Equation (6.3) requires usage of specific units, that is, θ in [kW], and h_k in [kW/(m²K)]. The estimation of heat release rate was based on a 10 kg of wooden crib test conducted in a more controlled environment. The heat release in the test was multiplied by 10 to get the estimated *HRR* in actual test. (Table 6.2)

Table 6.2 Input *HRR* Curve

Time(s)	0	715	790	985	1190	1462	1710	2090	2665
<i>HRR</i> (kW)	0	2370	2850	2410	1580	1070	493	168	64

The results are shown in Figure 6.1. The calculated maximum temperature was 500 °C for normal HDB and 350 °C for White-Block. Higher temperature in normal HDB configuration is due to the smaller value of ventilation factor. Therefore, the ventilation factor was the key factor which affected the fire room temperature. Equation (6.3) shows that the temperature is only a function of the *HRR* to the power of 2/3. Therefore, the shape of

Figure 6.1 is similar to the curve of *HRR* (Table 6.1). This method does not take into account of the depreciation of oxygen and the details of mass flow. In actual fire, the inflow and outflow of gas could be very different when fire is growing. The flow rate for incoming fresh air and outgoing smoke will depend on the depth of the smoke layer and other geometry parameters. Therefore, the accuracy of the result was limited. It can only serve as a check in prediction. More sophisticated software is needed for a better estimation.

Figure 6.1 The MQH Hand Calculation Results

6.3 CFAST Model Predictions

6.3.1 Assumptions of CFAST

CFAST is a zone-model software. For CFAST simulation, the whole compartment was separated in to five rooms according to Figure 6.2. The rooms were assumed to be rectangular boxes. The dimensions of the rooms are listed in Table 6.3.

Table 6.3 Dimensions of Rooms in CFAST Simulation Models

	Width (m)	Depth (m)	Height (m)
Rm1	3.95	3.20	2.65
Rm2	3.20	6.20	2.65
Rm3	3.20	6.20	2.65
Rm4	3.95	3.20	2.65
Rm5	3.95	3.20	2.65

Figure 6.2 Rooms and Opening and Their Identified Numbers

In CFAST, material thermal physical properties are assumed to be constant, although they actually vary with temperature. This assumption is made because data over the required temperature range is scarce, and the variation is relatively small for most materials.

All the doors and one window, W1-0, which was in Rm1, were assumed to be open. The ventilation factor of multi-opening compartment can be determined by the following formula.

$$f_v = \sum_i A_i \times \sqrt{\frac{\sum_i A_i H_i}{\sum_i A_i}} \tag{6.9}$$

The ventilation factors for Rm1 were 5.614 for normal HDB flat configuration, and 18.595 for white-block configuration. The fire load densities per total enclosure surface area for both cases were 34.5 MJ/m^3 .

Within CFAST, a fire is a source of fuel which is released at a specified rate. This fuel is converted into enthalpy and mass as it burns. Therefore, the wooden crib fire in the experiments was modelled as a simple fuel source.

Wooden crib fire is a kind of volumetric fire source. The near field entrainment rate of crib fire is difficult to predict. Therefore, the mathematics plume model described in CFAST is only suitable for far field calculation. The experimental data on this area is scarce. The same situation applied to the CFD model, FDS2.

6.3.2 CFAST Simulations Results

Figure 6.2 shows the rooms number indicated in the CFAST Results. The results of CFAST simulations are shown in *Figure 6.3* and *6.4*.

Figure 6.3 shows the temperature histories of all the rooms in normal HDB flat fire test. *Figure 6.3.a* shows the gas temperatures of upper and lower layer in the fire room. Maximum temperature in Rm1 was 645°C . Temperatures rose up to a peak and then dropped off. *Figure 6.3.b* and *c* show the results in the living room. Maximum upper-layer gas temperatures of Rm2 and Rm3 were 260°C and 202°C accordingly. *Figure 6.3.f* shows the smoke layer interface elevation histories. Rm1 had the lowest smoke layer interface elevation at 0.79 m from floor. Rm4 and Rm5 had lower interface elevation than Rm2 and Rm3, although they were far away from fire source.

Figure 6.4 shows the temperature histories of all the rooms in the white-block flat fire test. *Figure 6.4.a* shows simulation results in the fire room. Maximum temperature in Rm1

was 500 °C. Rm2 was connected to fire room directly and had a peak temperature of 341 °C. Rm3 and Rm4 were almost the same and had maximum temperatures of 269 and 274 °C. Figure 6.4.f is the smoke layer interface elevations histories of CF002 test. In this case, Rm5 had the lowest interface elevation at 0.86 m, although it was further away from origin of fire.

a) Temperature of Rm1

b) Temperature of Rm2

c) Temperature of Rm3

d) Temperature of Rm4

Figure 6.3 Temperature and Smoke Layer Interface for Normal HDB Flat Test

e) Temperature of Rm5

f) Smoke Layer Interface

Figure 6.3 Temperature and Smoke Layer Interface for Normal HDB Flat Test (cont.)

a) Temperature of Rm1

b) Temperature of Rm2

c) Temperature of Rm3

d) Temperature of Rm4

Figure 6.4 Temperature and Smoke Layer Interface for White-Block Flat Test

Figure 6.4 Temperature and Smoke Layer Interface for White-Block Flat Test (cont.)

In general, the CFAST results are higher than MQH perditions especially in white-block case. The CFAST results are comparing well with the test results even the prediction is higher. The smoke layer dropped down to one meter high. However, experiment shows that the smoke layer was quite high, which was above 1.55 m. Both results show that CFAST under-estimated the heat lost and mass transfer. It predicted a higher temperature and lower smoke layer. However, the results are in the safe side.

6.4 FDS2 Model Predictions

6.4.1 Assumptions of FDS2

The fire tests were also reconstructed using FDS2, which is a CFD code for fire modelling. The surfaces of the compartment, including the walls, ceilings and floors were required to input as rectangular blocks. Six coordinates were needed to identify a rectangular block in space. The complex geometries for both cases were constructed as shown in *Figure 6.1*. Altogether, 36 blocks were input to model the boundaries of the compartments.

The accuracy with which fire dynamics can be simulated partly depends on the number of cells that can be incorporated into the simulation. In these cases, the grid number was $80 \times 60 \times 20$, with a grid dimension $0.17 \times 0.17 \times 0.15$ m.

Fire source was indicated as a green box in the *Figure 6.5*, which generated the heat according to *Table 6.3*. The green box acted like a burner; its height was the same as half of the wooden crib height in the compartment fire tests.

a) Normal Configuration

b) White-Block Configuration

Figure 6.5 The Computational Fluid Dynamic Simulation Models of Compartment Fire Tests

6.4.2 FDS2 Simulations Results

For FDS2 modelling, user must specify the locations of the results he wants before running the program. Therefore, the locations and quantities to be measured were inputted. The locations of point measurement are indicated in *Figure 6.6*.

The simulation results of FDS2 are shown in *Figure 6.7* and *6.8*. The point numbers in *Figure 6.7* and *6.8* are the same as those in *Figure 6.6*. The channel numbers, “CH####”, have the same locations as the channel numbers for thermocouples, “D####”, in *Figure 6.5* and *6.6*. In *Figure 6.7* and *6.8*, *a-f* show the temperature predictions in the fire room, Rm1. In *Figure 6.7* and *6.8*, *g-i* are the temperature predictions in living room, Rm2 and Rm3. *Figure 6.7* and *6.8 j* shows the oxygen concentration in fire room at various locations. *Figure 6.7* and *6.8 k* and *m* show the carbon dioxide and carbon monoxide concentrations variations along the smoke path 1-7-9. *Figure 6.7* and *6.8 l* and *n* are the carbon dioxide and carbon monoxide concentrations in the fire room.

Figure 6.7.a shows the temperature histories of five elevations along point 1. The highest point had two peaks, at about 600 and 1200 seconds. The drop in temperature was due to a lack of oxygen at 900 seconds. This can be seen from *Figure 6.7.j*. At around 900 seconds, oxygen concentration in the fire room dropped to zero. When the gases cooled down, fresh air flowed into the fire room and the fire regained its size again. In the white-block case, minimum oxygen concentration went down to about 3% in mol ratio. Oxygen was available for burning and hence only one peak was observed in the temperature curves.

The maximum temperature predict in FDS for normal block was quite similar to the results obtained in test, around 700°C. In the white-block case, the predicted temperature was much higher than the experiment. However, the oxygen was calculated to be not sufficient for burning. This is not the case in the experiment. The difference may due to the over-estimation of *HRR*.

Figure 6.6 Locations of Points For FDS2 Simulations Results

a) Enlarge of Point 1 Temperatures graph

Figure 6.7 FDS2 Simulation Results for Normal Flat

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a) Point 1 Temperatures

b) Point 2 Temperature

c) Point 3 Temperature

d) Point 4 Temperature

e) Point 6 Temperature

f) Point 6 Temperature

Figure 6.7 FDS2 Simulation Results for Normal Flat (cont.)

g) Point 6 Temperature

h) Point 8 Temperature

i) Point 9 Temperature

j) Point 1,3,4,6 O₂

k) Point 1-7-9 CO₂

l) Point 3-4,6 CO₂

Figure 6.7 FDS2 Simulation Results for Normal Flat (cont.)

m) Point 1-7-9 CO

n) Point 3-4,6 CO

Figure 6.7 FDS2 Simulation Results for Normal Flat (cont.)

a) Enlarge of Point 1 Temperatures

a) Point 1 Temperatures

b) Point 2 Temperature

Figure 6.8 FDS2 Simulation Results for White-Block Flat

c) Point 3 Temperature

d) Point 4 Temperature

e) Point 5 Temperature

f) Point 6 Temperature

g) Point 7 Temperature

h) Point 8 Temperature

Figure 6.8 FDS2 Simulation Results for White-Block Flat (cont.)

i) Point 9 Temperature

j) Point 1,3,4,6 O₂

k) Point 1-7-9 CO₂

l) Point 3-4,6 CO₂

m) Point 1-7-9 CO

n) Point 3-4,6 CO

Figure 6.8 FDS2 Simulation Results for White-Block Flat (cont.)

The CFD results showed a more homogeneous upper layer in the fire room, since the top two temperature curves for each location were closer to the other. The concentration of oxygen in the fire room, represented by location 1, 3, 4 and 6, is shown in figure *j* of 6.7 and 6.8. Figure 6.7 and 6.8 *k-n* are the concentrations of Carbon Dioxide and Carbon Monoxide. The curves on smoke path, points 1-7-9, varied according to the distance to the fire source.

6.5 Comparisons of Room Temperature Histories

The average temperatures of upper and from actual experiments, MQH method, CFAST and FDS2 simulations are drawn in Figure 6.9. However, the above models were not able to model the actual experiment closely. The range of differences for the maximum average upper layer temperature was from 100 to 243 °C (Table 6.4 and Figure 6.9). It was observed that the temperature curve was closely dependent on the heat release curve in zone modelling. The reason is that the internal energy of gas is directly proportional to the gas temperature, in the case of constant pressure. And the energy stored in the gas is strongly dependent on the heat generated from fire. Therefore, better simulation results could be expected if better *HRR* curve was supplied.

a) CF001

b) CF002

Figure 6.9 Comparison of Upper-Layer Temperature Results

Table 6.4 Comparison of Maximum Upper-Layer Temperature in Fire Room [°C]

	Experiment		MQH		CFAST		FDS2	
	Nor	WB	Nor	WB	Nor	WB	Nor	WB
Average Upper Layer Temperature	430	400	500	350	645	500	703	643
Difference	-	-	+70	-50	+215	+100	+273	+243
Average Lower Layer Temperature	93	137	-	-	155	87	128	120
Difference	-	-	-	-	+62	-50	+35	-17
Nor – Normal HDB Flat								
WB – White-Block Flat								

Table 6.5 Comparison of Maximum Upper-Layer Temperature in Living Room [°C]

	Experiment		CFAST		FDS2	
	Nor	WB	Nor	WB	Nor	WB
Rm2 (Pt. 7)	350	350	260	341	480	640
Rm3 (Pt. 9)	130	190	202	269	280	380

Table 6.4 shows the comparisons of CFAST and FDS2 simulations with experimental results in the fire rooms. Table 6.5 shows the comparisons in the living room. In the living room, the temperature result at point 7 was used to represent Rm2 and point 9 was used to represent Rm3. The maximum temperature of the top thermocouple of point 7 and 9 were compared in Table 6.5. The result for CFAST was under-predicted. The mass transfer between the two rooms, room of fire origin and living room was under estimated.

6.6 Comparison of Maximum Ceiling Jet Temperatures

The maximum temperatures at highest position of various locations were compared in Figure 6.10 and 6.11. For normal flat test, CFAST predicted an average upper-layer temperature of 645°C, and the actual results gave the range of 420 to 740°C. CFAST

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predictions were within the range of variation. For white-block test, CFAST predicted 500°C in the fire room. This was also in the range of 370 to 610°C for actual tests. However, FDS2 predicted a relatively higher temperature. CFAST predicted the maximum temperature reasonably well.

a) Experimental Results

(Maximum temperature of the top thermocouples registered in CF001 test)

b) CFAST Predictions

(Maximum temperature of upper-layer in CFAST model for CF001 test)

Figure 6.10 Comparisons of Maximum Temperatures for Normal HDB Flat Test

c) FDS2 Predictions

(Maximum temperature of the top measurement points in FDS2 model for CF001 test)

NIST Smokeview 2.0 - December 9, 2001, CFTM007_1200_00.q

d) Detail Contours of FDS2 Predictions

(Maximum temperature at the ceiling level in FDS2 model for CF001 test)

Figure 6.10 Comparisons of Maximum Temperatures for Normal HDB Flat Test (cont.)

a) Experimental Results

(Maximum temperature of the top thermocouples registered in CF002 test)

b) CFAST Predictions

(Maximum temperature of upper-layer in CFAST model for CF002 test)

Figure 6.11 Comparisons of Maximum Temperatures for White-Block Flat Test

c) FDS2 Predictions

(Maximum temperature of the top measurement points in FDS2 model for CF002 test)

NIST Smokeview 2.0 - December 9, 2001, CFTM008_1200_01.q

d) Detail Contours of FDS2 Predictions

(Maximum temperature at the ceiling level in FDS2 model for CF002 test)

Figure 6.11 Comparisons of Maximum Temperatures for White-Block Flat Test (cont.)

In the fire room, Rm1, both CFAST and FDS2 gave high temperature predictions compared to actual test results, except for the lower-layer temperature for white-block. From *Table 6.5*, *Figure 6.10* and *6.11*, both programs suggested higher temperature in the living room (Rm2 and Rm3) in white-block than in normal flat. The reason was due to the larger opening between the fire room and the living room in white-block. The heat from fire will be much easier to transfer to the living room in white-block flat. However, the experimental results did not show much difference. The maximum temperature in Rm3 for white-block case was around 190°C, which was 50°C higher than in normal flat. In Rm2, the situations were even reverse; higher temperature results in the normal flat. The setup of temperature measurement for Rm2 was that the thermocouple might be directly submerged in the hot gas out flow from fire room. The temperature would be higher but not representative of the average value in Rm2.

6.7 Comparisons of Temperature Profiles along Smoke Path

The temperature profiles shown in *Figure 4.18* in the experiments were compared with the prediction of CFAST and FDS2. The slices of comparison are illustrated in *Figure 6.12*. The comparisons of the profiles were conducted at three stages in each test, the developing stage, the fully developed stage and the decaying or suppression stage. The time for the fire to reach the three stages were different for each model. The selected time of comparison is shown in *Table 6.6*. The different time chosen because the time interval for the fire to developed the stage were different. The difference came from the prediction of the *HRR* curve.

Table 6.6 The Selected Time For Temperature Profiles Comparisons (in seconds)

	CF001			CF002		
	Developing stage	Fully developed	Decaying/ suppression	Developing stage	Fully developed	Decaying/ suppression
Experiment	1100	1500	1720	1200	1700	2040

CFAST	600	900	1800	600	900	1800
FDS2	600	1200	1800	600	900	1800

a) Plan View for CF001

b) Plan View for CF002

c) Distances and Thermocouple Tree along Path 1-2-7-8-9

d) The Corresponding Room in CFAST along Path 1-2-7-8-9

Figure 6.12 Smoke Outflow Path 1-2-7-8-9

Figure 6.12 illustrates the locations and plan view of the smoke outflow path 1-2-7-8-9. The line passed through Rm1, Rm2 and Rm3. Because the two models have different assumptions, the output results were also different. In FDS2, the temperature history of each measuring point was given. Therefore, at a particular instant of time, the temperatures at some points on the slice along path 1-2-7-8-9 were known. This was similar to the situation of the fire test results. An analysis software MatLab was employed to draw the contour lines. (*Figure 6.12.c*) On the other hand, CFAST assumes that the gas in a room is separated into two distinct layers. Hence only the layer interface elevation and layer temperatures were provided in the output and they will be shown in the slice diagrams. (*Figure 6.12.d*)

The comparisons are shown in *Figure 6.13* to *6.18*. In each group of *Figures*, there are three sub-figures. The first one is the temperature contour obtained from the experiments. The second one is the temperature contour from FDS2 simulation at the same stage. The third one shows the results of CFAST predictions. The horizontal solid lines indicate the elevations of smoke layer interface. The number above the solid line is the upper-layer temperature while the one below is the lower-layer temperature at that time.

Both CFAST and FDS2 were able to reproduce a similar temperature pattern as the actual fire tests. In the contour line drawing, if the contour lines were far away from each other, that means the temperature at that area was uniform at that region. On the other hand, if the contour lines were close to each other, the gas experienced a steep temperature gradient. Steep temperature gradient appeared in most of the contour line drawings and it indicated the separation of the smoke layer and cool air. The results showed that both models were able to predict the smoke layer interface elevation closely. FDS2 gave a relatively higher prediction in temperature. However, the temperature predictions from CFAST were reasonably good.

a) Experimental Temperature Profiles of The Developing Stage
(CF001, 1100 seconds)

b) FDS2 Predictions on Temperature Profiles of The Developing Stage
(CF001, 600 seconds)

c) CFAST Predictions on Temperature Profiles of The Developing Stage
(CF001, 600 seconds)

Figure 6.13 Comparison of Temperature Profiles along Path 1-2-7-8-9 at Developing Stage in Test CF001

a) Experimental Temperature Profiles of The Fully Developed Stage
(CF001, 1500 seconds)

b) FDS2 Predictions on Temperature Profiles of The Fully Developed Stage
(CF001, 1200 seconds)

c) CFAST Predictions on Temperature Profiles of The Fully Developed Stage
(CF001, 900 seconds)

Figure 6.14 Comparison of Temperature Profiles along Path 1-2-7-8-9 at Fully Developed Stage in Test CF001

a) Experimental Temperature Profiles of The Suppression Stage
(CF001, 1720 seconds)

b) FDS2 Predictions on Temperature Profiles of The Decaying Stage
(CF001, 1800 seconds)

c)) CFAST Predictions on Temperature Profiles of The Decaying Stage
(CF001, 1800 seconds)

Figure 6.15 Comparison of Temperature Profiles along Path 1-2-7-8-9 at Decaying or Suppression Stage in Test CF001

a) Experimental Temperature Profiles of The Developing Stage
(CF002, 1200 seconds)

b) FDS2 Predictions on Temperature Profiles of The Developing Stage
(CF002, 600 seconds)

c) CFAST Predictions on Temperature Profiles of The Developing Stage
(CF002, 600 seconds)

Figure 6.16 Comparison of Temperature Profiles along Path 1-2-7-8-9 at Developing Stage in Test CF002

a) Experimental Temperature Profiles of The Fully Developed Stage
(CF002, 1700 seconds)

b) FDS2 Predictions on Temperature Profiles of The Fully Developed Stage
(CF002, 900 seconds)

c) CFAST Predictions on Temperature Profiles of The Fully Developed Stage
(CF002, 900 seconds)

Figure 6.17 Comparison of Temperature Profiles along Path 1-2-7-8-9 at Fully Developed Stage in Test CF002

a) Experimental Temperature Profiles of The Suppression Stage
(CF002, 2040 seconds)

b) FDS2 Predictions on Temperature Profiles of The Decaying Stage
(CF002, 1800 seconds)

c) CFAST Predictions on Temperature Profiles of The Decaying Stage
(CF002, 1800 seconds)

Figure 6.18 Comparison of Temperature Profiles along Path 1-2-7-8-9 at Decaying or Suppression Stage in Test CF002

CHAPTER 7

CONCLUSIONS

7.1 Summary

In the first part of this project, plume tests in the non-Boussinesq range were conducted to obtain a mass flux function that took into account the effect of large density differences. New equations were proposed to take into account of this effect and the results were checked with the test data. In the second part of the project, actual fire tests in multiple compartments were conducted. Numerical software such as CFAST and FDS were used to obtain predictions and comparison with actual test data.

7.2 Plume Model

From the non-destructive PIV and PLIF tests, the following results were obtained. For pure jets, the decay constant for the mean centreline velocity k_{jw} , and the velocity width constant k_{jwg} were measured to be 6.369 and 80.4 respectively. The mean centreline concentration decay constant k_{jc} was from 3.584 to 5.094. The concentration width constant k_{jcg} varied from 41.785 to 60.467. Jets with lower initial momentum were observed to have a wider concentration width. The mass fluxes of dye were calculated to vary from 0.700 to 0.917 of the initial mass flux. The entrainment coefficient α was found to be around 0.0516 to 0.0585.

For plumes, the mean centreline vertical velocity decay constant k_{pw} , was measured to be 3.85. The velocity width constant varied from 113.2 to 229.6.

The mass flux formula was given by:

$$\begin{aligned}
 q = & \pi k_{pw} \eta_{pwg}^2 B_0^{1/3} (z - z_0)^{5/3} \rho_a \left(1 - \frac{k_{pc} B_0^{2/3} z^{-5/3}}{g} \right)^{2\gamma} \\
 & - \pi k_{pw} \frac{\eta_{pwc}^2 \times \eta_{pwg}^2}{\eta_{pwc}^2 + \eta_{pwg}^2} B_0^{1/3} (z - z_0)^{5/3} \left(1 - \frac{k_{pc} B_0^{2/3} z^{-5/3}}{g} \right)^{2\gamma} \left(\frac{k_{pc} B_0^{2/3} z^{-5/3}}{g} \rho_a \right)
 \end{aligned} \quad (7.1)$$

where the adopted values of k_{pw} , η_{pwg} , k_{pc} and η_{pwc} were 4.13, 0.105, 11.3 and 0.109 (Law and Wang 2000). The γ here is negative $1/2$.

The initial buoyancy flux of the equation (7.1) was converted to account for the initial condition of fire:

$$\begin{aligned}
 q = & \pi k_{pw} \eta_{pwg}^2 \left(\frac{\theta_t g}{\rho_0 c_p T_a} \right)^{1/3} (z - z_0)^{5/3} \rho_a \left(1 - \frac{k_{pc} \left(\frac{\theta_t g}{\rho_0 c_p T_a} \right)^{2/3} z^{-5/3}}{g} \right)^{2\gamma} \\
 & - \pi k_{pw} \frac{\eta_{pwc}^2 \times \eta_{pwg}^2}{\eta_{pwc}^2 + \eta_{pwg}^2} \left(\frac{\theta_t g}{\rho_0 c_p T_a} \right)^{1/3} (z - z_0)^{5/3} \\
 & \times \left(1 - \frac{k_{pc} \left(\frac{\theta_t g}{\rho_0 c_p T_a} \right)^{2/3} z^{-5/3}}{g} \right)^{2\gamma} \left(\frac{k_{pc} \left(\frac{\theta_t g}{\rho_0 c_p T_a} \right)^{2/3} z^{-5/3}}{g} \rho_a \right)
 \end{aligned} \quad (7.2)$$

The predictions from equation 7.3 were compared with the approaches by Heskestad and McCaffrey in Chapter 4. Given the time, this plume model can be inserted into fire zone software such as CFAST for the prediction of smoke layer elevation.

7.3 Multi-Compartment Fire Test

An exploratory study on compartment fire test and fire modelling was conducted. Two compartment fire experiments were conducted in HDB flats to compare the different fire behaviours in white-block and normal flat configurations. Wooden cribs around 109 kg were used as fuel. The gas temperatures at various locations were measured. The differences between the two experiments were compared. White-block flat had lower upper-layer temperature than normal flat. However, the situation in the connected room was reversed. The steepest temperature gradient for fully developed fire took place at the bottom of the smoke layer in the fire room and the area just outside the fire room.

The MQH (refer to McCaffrey, Quintiere, and Harkleroad) method does not take into account of the depreciation of oxygen and the details of mass flow. Therefore, the prediction was not accurate. It can only serve as a rough guide.

In general, the CFAST results are higher than MQH predictions especially for white-block case. The maximum temperature predicted by CFAST is higher compared with the test results. Results for both tests show that CFAST under-estimated the heat loss and mass transfer. CFAST predicted a higher temperature and a lower smoke layer which means the results are on the safe side. In the room that was connected to the fire room, CFAST under-predicted the hot-layer temperature. The mass transfer between the two rooms, room of fire origin and living room, was underestimated.

The CFD results showed a more homogeneous upper layer in the fire room, since the top two temperature curves for each location were closer to the other. The FDS predictions were different from test data. More studies are required if the program were to be used in practice. When compared CFAST with FDS, CFAST would be a much practical choice since it is simple and yet predicts quite well. For research purpose, FDS is more flexible and more inside of the fluid properties and movement.

7.4 Future Work

The research work has not been easy in these two years. A lot of time was spent on the instrumentation of the plume tests as well as the compartment fire test. The former was conducted in laboratory conditions, while the latter in field conditions. The research work was also delayed due to some accidents. For example, the laser for the plume test broke down twice during the experiments and the repair took about two months. In the compartment fire tests, the fabrication of thermocouple trees took around a month to finish.

The original objective of the project is to investigate the mixing characteristics of non-Boussinesq plumes. The improved understanding can then be applied to the simulations of fire-induced plume, with the compartment fire test data available for verification. However, the integration was not fully executed due to the time constraint.

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APPENDIX A COMPARTMENT FIRE TESTS RESULTS

A.1 The Spacing of Thermocouple Tree

A.2 Temperature Results for CF001, Normal Configuration

Figure A.1 Locations of Measuring Points for CF001

APPENDIX A

Table A.1 Location of Thermocouples and The Corresponding Channel IDs in Compartment Fire Tests

Measurement Location	x = (mm)	y = (mm)	z = 2550mm	z = 2050mm	z = 1550mm	z = 1050mm	z = 800mm
1	(-2000	-750)	D000	D001	D002	D003	D004
2	(-3000	-750)	D005	D006	D007	D008	D009
3	(-1234	2472)	D010	D011	D012	D013	D014
4	(-1469	3444)	D015	D016	D017	D018	D019
5	(-2800	1950)	D020	D021	D022	D023	D024
6	(-2800	3550)	D025	D026	D027	D028	D029
7	(-4975	200)	D030	D031	D032	-	-
8	(-6968	1425)	D033	D034	D035	-	-
9	(-8961	3050)	D036	D037	D038	-	-

Table A.2 Location and Elevation of Thermocouples and The Corresponding Series Number

	z = 2550mm	z = 2050mm	z = 1550mm	z = 1050mm	z = 800mm
1	V01641-2/02	V01640-2/02	V01624-2/02	V01639-2/02	V01620-2/02
2	V01630-2/02	V01628-2/02	V01623-2/02	V01621-2/02	V01618-2/02
3	V01635-2/02	V01634-2/02	V01622-2/02	V01629-2/02	V01619-2/02
4	V01632-2/02	V01633-2/02	V01625-2/02	V01612-2/02	V01613-2/02
5	V01636-2/02	V01631-2/02	V01627-2/02	V01614-2/02	V01616-2/02
6	V01637-2/02	V01638-2/02	V01626-2/02	V01615-2/02	V01617-2/02
7					
8					
9					

APPENDIX A

Table A.3 Temperature Results on Point 1

Date	Clock	D000	D001	D002	D003	D004
22/03/2002	16:28:07	29	29.2	29.2	29.2	29.3
22/03/2002	16:28:27	28.9	29.1	29.2	29.2	29.3
22/03/2002	16:28:47	31.5	30.8	30.5	29.7	29.8
22/03/2002	16:29:07	35.1	30.6	30	29.7	29.7
22/03/2002	16:29:27	36.7	31.9	30.8	29.8	29.9
22/03/2002	16:29:47	39.7	32.6	31	30.6	30.6
22/03/2002	16:30:07	121.9	82.2	66	50.5	61.7
22/03/2002	16:30:27	99.8	75.9	53.6	37.7	43
22/03/2002	16:30:47	75.2	65.1	40.9	32.8	34.8
22/03/2002	16:31:07	61	53.3	37.6	31.7	32.8
22/03/2002	16:31:27	59.4	48.1	35.9	32.2	32.6
22/03/2002	16:31:47	59.4	44.2	35.6	33.6	33.8
22/03/2002	16:32:07	56.1	41	34.6	33.1	32.9
22/03/2002	16:32:27	56.3	42.6	33.6	32.3	32.2
22/03/2002	16:32:47	56.5	42	33.4	32.2	32
22/03/2002	16:33:07	57.2	42.2	33.5	31.8	31.7
22/03/2002	16:33:27	56.7	43.6	33.4	31	30.9
22/03/2002	16:33:47	57.8	45	33.6	30.6	30.6
22/03/2002	16:34:07	143.1	53.3	43	37	37.6
22/03/2002	16:34:27	116.5	72.5	44.3	32.9	33.5
22/03/2002	16:34:47	83.9	60.4	44.4	30.8	31.2
22/03/2002	16:35:07	72.9	54.6	43.7	31	30.8
22/03/2002	16:35:27	72.5	51.8	37.4	30.8	30.6
22/03/2002	16:35:47	73	51.2	36.5	30.8	30.8
22/03/2002	16:36:07	76.9	52.5	35.4	31	31.1
22/03/2002	16:36:27	188.7	96.3	49.9	40.1	39.5
22/03/2002	16:36:47	131.7	89	43.6	38.1	36.4
22/03/2002	16:37:07	106.2	74.5	40.5	36.3	34.9
22/03/2002	16:37:27	86.3	63.9	36.9	34.1	33
22/03/2002	16:37:47	78	55.5	35.6	32.9	32.2
22/03/2002	16:38:07	79.5	51.8	35.1	33.3	32.6
22/03/2002	16:38:27	90.1	51.1	35.7	33.6	32.8
22/03/2002	16:38:47	93.5	54.3	34.9	32.7	32.3
22/03/2002	16:39:07	97.3	58.7	36.7	32.9	32.4
22/03/2002	16:39:27	110.7	68.7	42.5	33.7	33
22/03/2002	16:39:47	126.6	76.5	39.9	34.8	34.4

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22/03/2002	16:40:07	142.6	89.4	43.7	35.1	34.8
22/03/2002	16:40:27	153.2	96.6	45.1	35.5	34.7
22/03/2002	16:40:47	173.9	102.3	45.1	38.5	37.6
22/03/2002	16:41:07	189.6	106.6	44.6	40.3	38.7
22/03/2002	16:41:27	195.4	110.1	44.7	40.7	38.8
22/03/2002	16:41:47	206.6	113.4	46.2	39.1	37.5
22/03/2002	16:42:07	219.2	127.8	47.5	39.2	38
22/03/2002	16:42:27	227.8	136.4	48.4	40.8	39.2
22/03/2002	16:42:47	243.7	141.2	50	43.7	41.5
22/03/2002	16:43:07	249.3	152.9	49.8	43.3	41.7
22/03/2002	16:43:27	249.4	150.4	48.6	43	41.6
22/03/2002	16:43:47	267.1	148.5	50.5	44.8	43.4
22/03/2002	16:44:07	297.8	158.6	56.3	51.7	48.1
22/03/2002	16:44:27	291.5	165.8	53	46.3	44.5
22/03/2002	16:44:47	302.6	170.3	57.7	43.6	43.1
22/03/2002	16:45:07	323.2	184.8	55.5	46.5	46.1
22/03/2002	16:45:27	335.2	186.6	58.5	50.3	47.9
22/03/2002	16:45:47	347.6	198.2	58.2	47.6	46.8
22/03/2002	16:46:07	369.6	209.9	59.7	49.2	49.9
22/03/2002	16:46:27	378.3	219.6	63.1	52	50.5
22/03/2002	16:46:47	399	224.3	69.7	55.6	52.1
22/03/2002	16:47:07	424	243.6	76.2	61.5	56
22/03/2002	16:47:27	432	256.7	83.2	69.4	61.4
22/03/2002	16:47:47	432	252	86.8	75.6	67.4
22/03/2002	16:48:07	445.2	266.2	90.2	79	71.1
22/03/2002	16:48:27	454.5	272.5	92.4	84.8	75
22/03/2002	16:48:47	468.8	283.8	99	80.3	67
22/03/2002	16:49:07	477.7	289.9	99.8	82.6	70.8
22/03/2002	16:49:27	486.7	292.1	99.5	77.4	68.6
22/03/2002	16:49:47	488.9	292.9	100.5	73.3	66.6
22/03/2002	16:50:07	463.9	287.2	104.7	69.2	63.1
22/03/2002	16:50:27	509.6	299	106.2	69.5	63.7
22/03/2002	16:50:47	527.4	306.2	109.2	74.4	70
22/03/2002	16:51:07	549.6	319.6	113.4	76.3	70.9
22/03/2002	16:51:27	583.9	323.3	122.3	80.8	74.9
22/03/2002	16:51:47	606.1	322.8	127.7	95.1	83.3
22/03/2002	16:52:07	625.5	343	132.1	104.4	87.8
22/03/2002	16:52:27	659.5	345.4	139.3	103.2	84.8
22/03/2002	16:52:47	617	423.4	145.4	89	82.9
22/03/2002	16:53:07	648	453.5	156	96.7	88.9

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22/03/2002	16:53:27	699	444.8	159	113.1	99
22/03/2002	16:53:47	742.6	419.3	165.1	126.7	103.5
22/03/2002	16:54:07	727.4	449	172	133.7	104.7
22/03/2002	16:54:27	707	451.6	176	138.4	111.8
22/03/2002	16:54:47	719.6	454.8	180.4	137.9	97
22/03/2002	16:55:07	702.9	447.7	184.3	131.7	100.5
22/03/2002	16:55:27	695.8	457.1	188.1	131.5	109.5
22/03/2002	16:55:47	701.4	462.2	188.2	123.1	102.9
22/03/2002	16:56:07	692	452	188.2	131.5	113.8
22/03/2002	16:56:27	718.1	442.3	187.7	143.1	123.7
22/03/2002	16:56:47	667.7	454.3	184.9	118.4	104.4
22/03/2002	16:57:07	652.7	424.9	100.6	46.9	50.9
22/03/2002	16:57:27	145.8	150	56.3	52	45.6
22/03/2002	16:57:48	93	56.4	54.1	52.7	49.6
22/03/2002	16:58:07	123.7	70.2	50.7	36.6	33.1
22/03/2002	16:58:27	121.2	76	41.9	35.1	34
22/03/2002	16:58:47	100.8	52	43.6	41.3	42.3
22/03/2002	16:59:07	109.4	47.7	42.3	38.2	36
22/03/2002	16:59:27	118.1	47.4	40.6	36.3	35.1
22/03/2002	16:59:47	120.1	44.7	39.9	36.1	35
22/03/2002	17:00:07	122.9	45	39	36.2	35.5
22/03/2002	17:00:27	121.9	43.6	39.1	35.8	34.8
22/03/2002	17:00:47	121.3	43.6	37.9	34.8	33.8

Table A.4 Temperature Results on Point 2

Date	Clock	D005	D006	D007	D008	D009
22/03/2002	16:28:07	29.3	29.3	29.3	29.3	29.3
22/03/2002	16:28:27	29.2	29.3	29.3	29.3	29.3
22/03/2002	16:28:47	31.1	30	30.2	29.5	29.5
22/03/2002	16:29:07	34.1	29.8	29.9	29.5	29.5
22/03/2002	16:29:27	35.2	31.8	30.3	29.6	29.5
22/03/2002	16:29:47	37.7	32.3	30.3	29.9	29.8
22/03/2002	16:30:07	109.8	93.8	48.3	34.7	33.7
22/03/2002	16:30:27	96.1	81.8	37.7	35	34
22/03/2002	16:30:47	75.2	51.1	33.2	32.8	31.3
22/03/2002	16:31:07	60.3	47.3	31.8	32	31
22/03/2002	16:31:27	56.6	45.1	33.2	32.2	31.5
22/03/2002	16:31:47	56.5	41.9	35.2	33.5	32.1
22/03/2002	16:32:07	53.8	39.6	34.1	32.8	32
22/03/2002	16:32:27	54.4	40.3	32.8	31.9	31.3
22/03/2002	16:32:47	54.9	40.3	32.5	31.5	31.2
22/03/2002	16:33:07	54.8	37.4	32	31.3	31
22/03/2002	16:33:27	54.2	39.9	31	30.7	30.3
22/03/2002	16:33:47	55.6	34.9	30.7	30.5	30.2
22/03/2002	16:34:07	99.2	74.3	33.3	31.8	32.3
22/03/2002	16:34:27	105.7	82.1	31.6	30.8	30.8
22/03/2002	16:34:47	80.4	56.3	30.7	30.2	30.2
22/03/2002	16:35:07	69.1	51.8	30.7	30.3	30.1
22/03/2002	16:35:27	66.6	47.7	30.7	30.1	30
22/03/2002	16:35:47	67.7	50.7	30.6	30.2	30.1
22/03/2002	16:36:07	71.8	51	30.5	30.3	30.4
22/03/2002	16:36:27	163.8	102.6	36.5	32.7	33
22/03/2002	16:36:47	133.3	84.3	35.6	32.3	31.6
22/03/2002	16:37:07	104.4	66.1	34.4	32.2	31.6
22/03/2002	16:37:27	86.3	55.2	32.9	31.4	30.9
22/03/2002	16:37:47	76.1	47.8	32.4	31.5	30.9
22/03/2002	16:38:07	74.6	44.3	32.9	31.5	31.2
22/03/2002	16:38:27	82.6	41.5	32.7	31.5	31
22/03/2002	16:38:47	86.8	43.8	31.6	31.5	30.8
22/03/2002	16:39:07	89.1	47.2	31.2	31.3	30.9
22/03/2002	16:39:27	99.8	64.4	31.1	31.3	31.2
22/03/2002	16:39:47	115.5	75	31.2	31.8	31.9
22/03/2002	16:40:07	129.4	71.9	31.5	31.9	31.6

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22/03/2002	16:40:27	140.8	89.1	31.7	31.5	31.2
22/03/2002	16:40:47	157.9	90.5	35.3	33.5	33.3
22/03/2002	16:41:07	174.1	78.8	37.1	33.9	34
22/03/2002	16:41:27	177	80.5	36.4	33.6	33.5
22/03/2002	16:41:47	187.1	76.1	34.5	33	32.7
22/03/2002	16:42:07	194.7	93.8	34.4	33.1	32.8
22/03/2002	16:42:27	204.8	108.6	35.1	33.7	33.3
22/03/2002	16:42:47	219.6	117.1	36.9	34.8	34.6
22/03/2002	16:43:07	226.1	127.4	35.5	34.3	34.9
22/03/2002	16:43:27	224	163.5	36.4	35.6	35.1
22/03/2002	16:43:47	235.4	176.4	38.1	36.9	35.7
22/03/2002	16:44:07	263.5	162.3	42.9	38.9	37.9
22/03/2002	16:44:27	263	190.3	38.6	38	36.2
22/03/2002	16:44:47	262.8	213.9	37.2	36.7	36
22/03/2002	16:45:07	289.2	219.8	37.7	37.9	38
22/03/2002	16:45:27	294.5	233.1	41.2	39.3	37.9
22/03/2002	16:45:47	306.9	261	39	37.7	37.4
22/03/2002	16:46:07	326.9	269.4	39.2	39.3	38.6
22/03/2002	16:46:27	332.4	271.8	41	39.6	38.9
22/03/2002	16:46:47	355	278.2	45.7	40	39.5
22/03/2002	16:47:07	373.8	280.5	48.8	40.9	41.3
22/03/2002	16:47:27	385.5	280.9	53.5	43.7	43
22/03/2002	16:47:47	381.8	276.6	59.7	47.3	45.1
22/03/2002	16:48:07	394	281.4	63.9	47.5	44.4
22/03/2002	16:48:27	400.3	288.9	66.5	48.2	45.8
22/03/2002	16:48:47	413.1	300.4	56.8	49.1	45.3
22/03/2002	16:49:07	430	312.4	60.5	50.4	49.7
22/03/2002	16:49:27	439.6	308.8	57.2	49.9	47.6
22/03/2002	16:49:47	436.4	336	54.2	47.4	45.8
22/03/2002	16:50:07	406.8	362	52.6	50	45.7
22/03/2002	16:50:27	440.9	364.2	56.5	49	45.2
22/03/2002	16:50:47	462.7	366.2	59.9	51.5	47.9
22/03/2002	16:51:07	476	360.2	59.6	50.9	47.9
22/03/2002	16:51:27	501.3	374.6	59.8	51.2	48.4
22/03/2002	16:51:47	525.4	355.3	71.5	55.8	53.1
22/03/2002	16:52:07	548.6	376.6	78.9	57.1	56.4
22/03/2002	16:52:27	564.3	379.1	73.8	58.1	53.5
22/03/2002	16:52:47	555.7	431.6	69.9	62.2	50.8
22/03/2002	16:53:07	573.3	467.8	79.6	59.7	50.1
22/03/2002	16:53:27	608.1	422.3	87.3	62.8	62.1

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22/03/2002	16:53:47	650.4	425	97.2	64.6	64.5
22/03/2002	16:54:07	649.3	424.1	95.2	69	63.7
22/03/2002	16:54:27	638.7	445.8	91.5	70.5	63.8
22/03/2002	16:54:47	662.2	464.3	100.9	71.5	64.9
22/03/2002	16:55:07	647.1	483.6	90.2	72.1	61.6
22/03/2002	16:55:27	656.3	488.8	94.9	75.7	67.8
22/03/2002	16:55:47	648	500.5	96.6	72	65.8
22/03/2002	16:56:07	632.3	483.9	101.8	77.4	75.5
22/03/2002	16:56:27	645	475.1	113.4	75.5	67.2
22/03/2002	16:56:47	616.4	510.8	91.3	69.3	60.4
22/03/2002	16:57:07	569.1	477.3	64	36.9	47.6
22/03/2002	16:57:27	163.1	164.4	83.2	66.5	41
22/03/2002	16:57:48	107.8	102.1	75.1	51.1	42.9
22/03/2002	16:58:07	110.7	78.7	55.4	42.3	37.4
22/03/2002	16:58:27	99	61.7	47.2	42.4	40.1
22/03/2002	16:58:47	91.9	52.8	43.5	44.7	41.2
22/03/2002	16:59:07	93	55.6	43.5	40.6	35.7
22/03/2002	16:59:27	99.4	58.1	43.8	40.3	34.2
22/03/2002	16:59:47	96.2	57.2	43.4	39.3	33.4
22/03/2002	17:00:07	95.7	56.5	44	40	34.9
22/03/2002	17:00:27	94.5	56.7	44	39.9	34.8
22/03/2002	17:00:47	94.3	56	44	39.8	33.4

APPENDIX A

Table A.5 Temperature Results on Point 3

Date	Clock	D010	D011	D012	D013	D014
22/03/2002	16:28:07	29.2	29.5	29.6	29.6	29.7
22/03/2002	16:28:27	28.9	29.2	29.4	29.4	29.5
22/03/2002	16:28:47	30.1	29.8	29.6	29.6	29.7
22/03/2002	16:29:07	32.1	30.1	29.8	29.7	29.8
22/03/2002	16:29:27	33.2	31.7	31	30.2	29.9
22/03/2002	16:29:47	35.2	32.6	31.2	30.2	30
22/03/2002	16:30:07	105.1	70.2	54.6	37.6	35.6
22/03/2002	16:30:27	93	69.2	47.5	37.2	34.9
22/03/2002	16:30:47	72.8	58	41.7	35.6	34
22/03/2002	16:31:07	58.8	49.2	38.6	34.2	33
22/03/2002	16:31:27	54.3	45.1	36.2	33.6	32.7
22/03/2002	16:31:47	53.4	42.8	34.4	32.8	32.2
22/03/2002	16:32:07	51.7	41.3	33.5	32.3	32
22/03/2002	16:32:27	51.2	40.7	33.3	32.1	31.8
22/03/2002	16:32:47	51.8	40	32.9	32	31.8
22/03/2002	16:33:07	52.8	40.4	32.7	31.7	31.5
22/03/2002	16:33:27	53	39.9	32.4	31.4	31.1
22/03/2002	16:33:47	53.6	39.6	32.2	31.1	30.9
22/03/2002	16:34:07	100.6	50.1	35.3	32.5	32.5
22/03/2002	16:34:27	98.9	63.6	38.6	32.8	32.6
22/03/2002	16:34:47	76.9	54.3	37.1	32.4	32
22/03/2002	16:35:07	64.4	47.8	37.1	32	31.6
22/03/2002	16:35:27	61.2	45.7	35.7	31.8	31.5
22/03/2002	16:35:47	61.7	44.8	34.5	31.7	31.3
22/03/2002	16:36:07	65	45.4	34.1	31.6	31.2
22/03/2002	16:36:27	152	80.2	42.8	34.8	33.8
22/03/2002	16:36:47	125.2	70.6	40.7	34	33.3
22/03/2002	16:37:07	101.5	60.1	38.2	33.5	32.8
22/03/2002	16:37:27	85.8	50.7	36.4	33	32.5
22/03/2002	16:37:47	75.8	45.4	35	32.5	32.1
22/03/2002	16:38:07	73.6	44	33.1	32.2	31.9
22/03/2002	16:38:27	77.4	43.7	33.7	32.2	32
22/03/2002	16:38:47	78.3	44	33.8	32.4	31.8
22/03/2002	16:39:07	81	47.1	34.6	32.7	32
22/03/2002	16:39:27	88.4	51.2	35.9	32.9	32.2
22/03/2002	16:39:47	99.6	56.6	36.7	33.4	32.6
22/03/2002	16:40:07	109.8	62.1	38.3	34.1	33

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22/03/2002	16:40:27	120.4	67.4	39	34.5	33.1
22/03/2002	16:40:47	137.9	72	37.9	35	33.7
22/03/2002	16:41:07	151.9	76.2	38.3	35.5	34
22/03/2002	16:41:27	160.6	74.6	39.1	36.3	35
22/03/2002	16:41:47	167.4	71.3	39.8	36.3	35
22/03/2002	16:42:07	176.6	76	39.5	36.5	35
22/03/2002	16:42:27	185.7	77	40.2	37.4	35.5
22/03/2002	16:42:47	196.7	86	41.3	38.2	36.2
22/03/2002	16:43:07	202.2	87.7	41.5	38.3	36.5
22/03/2002	16:43:27	200.4	98.4	43.1	39.1	37.1
22/03/2002	16:43:47	208	112.2	45.4	40.5	37.9
22/03/2002	16:44:07	232	113.8	46.4	39.3	36.8
22/03/2002	16:44:27	231.9	115.8	45.6	40.1	37.6
22/03/2002	16:44:47	234.7	128.9	48	42	39.1
22/03/2002	16:45:07	245.1	133.4	50.1	43.5	39.9
22/03/2002	16:45:27	247.3	142.5	51.7	44.5	40.5
22/03/2002	16:45:47	260.1	147.2	52.8	45.7	41.6
22/03/2002	16:46:07	269.7	157.5	54	46.8	42.3
22/03/2002	16:46:27	277.2	161.8	55.4	48.2	43.4
22/03/2002	16:46:47	290.9	166.2	56.7	49.4	44.2
22/03/2002	16:47:07	304.1	174.4	58.8	51.8	45.8
22/03/2002	16:47:27	318.5	181.1	59.6	49.1	45.7
22/03/2002	16:47:47	326.7	178.6	62.2	48.7	45.6
22/03/2002	16:48:07	331.7	194	62.7	49.4	44.6
22/03/2002	16:48:27	341.9	202.9	64.8	48.7	45.3
22/03/2002	16:48:47	337.9	206.2	63.5	51.7	47.3
22/03/2002	16:49:07	345.5	220	64.1	53.8	49
22/03/2002	16:49:27	347.4	224.6	65.3	53.3	49.1
22/03/2002	16:49:47	343.6	234.2	65.9	53.7	48.8
22/03/2002	16:50:07	314.2	211.1	76.1	57.3	51.4
22/03/2002	16:50:27	314.1	221.1	78.4	58.2	52.3
22/03/2002	16:50:47	326.9	233.8	75.7	59.2	53
22/03/2002	16:51:07	336.5	241.5	78.3	61.2	54.8
22/03/2002	16:51:27	353.9	252.5	80.1	62.9	56.8
22/03/2002	16:51:47	376.6	262.6	83.7	65.1	58.6
22/03/2002	16:52:07	383.3	261.3	83.7	62.9	56.7
22/03/2002	16:52:27	388.3	270.2	83.1	66.1	59.3
22/03/2002	16:52:47	375.3	284	87.1	65.9	60
22/03/2002	16:53:07	386.8	285.3	96.4	66.3	59.2
22/03/2002	16:53:27	426.1	307.3	97.7	71.4	61.6
22/03/2002	16:53:47	441.1	313.9	98.1	69.8	60.3

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22/03/2002	16:54:07	446.4	311	101.1	72.3	65.4
22/03/2002	16:54:27	444.6	306.5	100.9	78.8	69.9
22/03/2002	16:54:47	451.3	309.4	105.8	81.4	72.4
22/03/2002	16:55:07	433.7	306.4	105.4	78.7	69.3
22/03/2002	16:55:27	430	301.5	105.3	81.3	72.5
22/03/2002	16:55:47	410.1	299	102.8	82.6	74.6
22/03/2002	16:56:07	426.6	312.6	102.2	81.6	73.4
22/03/2002	16:56:27	437	317.6	106.4	81	70.5
22/03/2002	16:56:47	404.5	305.5	105.8	80.5	70.3
22/03/2002	16:57:07	372.8	285.9	109.9	77	62.2
22/03/2002	16:57:27	107.9	137	77.3	68.7	68.1
22/03/2002	16:57:48	71.4	85.9	66.1	56.9	53.9
22/03/2002	16:58:07	81.4	77.7	64.3	51.7	45.2
22/03/2002	16:58:27	71.5	68.8	60	49.7	44.7
22/03/2002	16:58:47	65.7	62.1	50.4	47.1	46.1
22/03/2002	16:59:07	72.2	59.3	43	40	38.2
22/03/2002	16:59:27	82.9	57.5	44.7	38.1	38.1
22/03/2002	16:59:47	89.3	53.5	44.9	37.3	39.5
22/03/2002	17:00:07	91.3	52.7	44.5	37.8	39.3
22/03/2002	17:00:27	90.8	52.3	44.4	39.6	40.3
22/03/2002	17:00:47	89.3	51.3	43.6	40.3	40.4

Table A.6 Temperature Results on Point 4

Date	Clock	D015	D016	D017	D018	D019
22/03/2002	16:28:07	29.8	29.8	29.9	29.8	29.8
22/03/2002	16:28:27	29.5	29.6	29.6	29.6	29.5
22/03/2002	16:28:47	30.4	30	29.8	29.7	29.7
22/03/2002	16:29:07	32.5	30.8	30.1	29.9	29.9
22/03/2002	16:29:27	31.3	31.2	30.8	30	30
22/03/2002	16:29:47	34	32.4	31.3	30.2	30
22/03/2002	16:30:07	108	83.7	58	38.4	35.6
22/03/2002	16:30:27	94.2	70.7	47.6	38.3	36.4
22/03/2002	16:30:47	74	57.7	40.4	35.2	34.3
22/03/2002	16:31:07	58.8	48	36.8	33.5	33
22/03/2002	16:31:27	52.1	39.8	33.9	32.6	32.4
22/03/2002	16:31:47	49.3	35.3	31.9	32	32
22/03/2002	16:32:07	49.8	40	32.4	31.5	31.4
22/03/2002	16:32:27	49.4	40.9	32.6	31.7	31.7
22/03/2002	16:32:47	50	41.5	32.3	31.3	31.6
22/03/2002	16:33:07	50.8	41.8	31.9	30.7	31
22/03/2002	16:33:27	50.9	41.8	31.8	30.9	31
22/03/2002	16:33:47	51.9	42.4	31.5	30.8	30.8
22/03/2002	16:34:07	91.2	60.3	35	32.2	32.2
22/03/2002	16:34:27	103.1	71.4	36.9	32.7	32.3
22/03/2002	16:34:47	77.2	58.6	35.6	32.4	31.9
22/03/2002	16:35:07	64.1	52.4	35.2	32.2	31.7
22/03/2002	16:35:27	60.2	49.3	34.2	31.7	31.4
22/03/2002	16:35:47	59.9	48.5	33.5	31.4	31.2
22/03/2002	16:36:07	62.2	49	32.8	31.3	31.2
22/03/2002	16:36:27	151.5	90.5	36.7	33.2	32.9
22/03/2002	16:36:47	124.8	72.8	36.5	33.7	33
22/03/2002	16:37:07	99.5	60.2	33.7	33.2	32.7
22/03/2002	16:37:27	83.7	50.1	33.4	32.1	32.1
22/03/2002	16:37:47	73	45	32.4	31.7	31.8
22/03/2002	16:38:07	69.5	37.2	31.5	31.5	31.5
22/03/2002	16:38:27	71.6	41.9	32.4	31.7	31.6
22/03/2002	16:38:47	74.4	47.2	33	31.9	31.8
22/03/2002	16:39:07	78.1	52.7	34.1	32.3	32
22/03/2002	16:39:27	84.9	56.8	35	32.5	32.3
22/03/2002	16:39:47	95.8	66.6	35.9	33	32.7
22/03/2002	16:40:07	104.8	72.3	36.5	33.2	32.9

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22/03/2002	16:40:27	112.9	80.5	37	33.4	33.1
22/03/2002	16:40:47	125	85.9	34.4	33.7	33.5
22/03/2002	16:41:07	135.9	94.7	33.8	33	33.7
22/03/2002	16:41:27	142.5	97.6	34.5	33.9	34.3
22/03/2002	16:41:47	150.4	99.5	36.3	34.5	34.6
22/03/2002	16:42:07	158.9	106.3	37.7	34.8	35.1
22/03/2002	16:42:27	165.7	116.3	37.9	35.3	35.6
22/03/2002	16:42:47	174	121.2	36.2	35.8	36
22/03/2002	16:43:07	179.6	127.8	38.1	36.1	36.3
22/03/2002	16:43:27	180.8	135.6	39.2	36.3	36.4
22/03/2002	16:43:47	186.6	139.9	42.3	37.1	37
22/03/2002	16:44:07	204.6	147.4	38.6	36.7	37.1
22/03/2002	16:44:27	208	151.6	41.4	37.6	37.3
22/03/2002	16:44:47	215	163.7	44.4	38.3	38.2
22/03/2002	16:45:07	219	167.1	45	38.8	39
22/03/2002	16:45:27	222.2	170.4	46.5	39.6	39.2
22/03/2002	16:45:47	235	181.5	47.7	40.2	40
22/03/2002	16:46:07	243.1	186.3	48	40.7	40.8
22/03/2002	16:46:27	248.7	192.9	49.4	41.8	42.1
22/03/2002	16:46:47	257.1	202.7	49.5	41.7	42.2
22/03/2002	16:47:07	268.8	209.2	45.9	40.6	42.6
22/03/2002	16:47:27	275.7	223.9	43.9	42.5	44.1
22/03/2002	16:47:47	281.1	220.2	43.1	42.9	45.3
22/03/2002	16:48:07	285.6	225.7	42.3	42.6	45
22/03/2002	16:48:27	296.8	224.3	42.8	44.2	45.9
22/03/2002	16:48:47	296.5	230.9	48.3	41.7	44.3
22/03/2002	16:49:07	300.6	243.9	44.1	43.1	45.3
22/03/2002	16:49:27	302.3	246.1	49.6	43.9	46.8
22/03/2002	16:49:47	303	259.7	57.4	46.1	46.8
22/03/2002	16:50:07	289.9	245	69.9	49.2	48.9
22/03/2002	16:50:27	289.4	252.6	68.5	52	51.7
22/03/2002	16:50:47	295	262.6	69	51.8	51.9
22/03/2002	16:51:07	300.9	273.2	70.7	48.8	50.1
22/03/2002	16:51:27	310.3	268.9	72.8	51.8	53
22/03/2002	16:51:47	325.1	278.3	52.8	52.9	55.6
22/03/2002	16:52:07	332.3	300.7	51.7	49.6	53.8
22/03/2002	16:52:27	341.3	302.7	59.8	45.7	49.8
22/03/2002	16:52:47	341.6	305.4	73.6	51.8	52.9
22/03/2002	16:53:07	352.5	303.5	85.8	51.1	54.6
22/03/2002	16:53:27	375.7	329.3	74.4	48.9	53.6
22/03/2002	16:53:47	385.5	332.9	62	55.9	59.5

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22/03/2002	16:54:07	389.1	329.4	67.3	56.4	60.9
22/03/2002	16:54:27	393	318.3	78.1	56	60.3
22/03/2002	16:54:47	391.6	310.9	86.3	58.5	61.2
22/03/2002	16:55:07	382.4	310.2	86.8	56.8	58.1
22/03/2002	16:55:27	378.2	318	92.5	50.1	51.9
22/03/2002	16:55:47	361.8	319	94.8	46.3	48.6
22/03/2002	16:56:07	370.2	331.3	96.2	47.4	49.5
22/03/2002	16:56:27	380.3	337.1	93.7	47.5	53.4
22/03/2002	16:56:47	363.2	321.8	94.6	55.7	57.9
22/03/2002	16:57:07	337.4	294.1	94.1	53.5	54.5
22/03/2002	16:57:27	108.3	100.3	66.5	57.7	60.6
22/03/2002	16:57:48	81.5	67.7	49.1	41.5	46.4
22/03/2002	16:58:07	91.5	71.5	51.9	44.9	44.8
22/03/2002	16:58:27	85.7	67.7	53.6	43	42.2
22/03/2002	16:58:47	75.4	62.2	51.6	44.7	43.5
22/03/2002	16:59:07	81.1	59.3	46.5	36	37.3
22/03/2002	16:59:27	86.2	57.2	42.8	36.1	36
22/03/2002	16:59:47	92.7	54.7	40	37.4	36.7
22/03/2002	17:00:07	93	52.3	37.6	38.1	37.7
22/03/2002	17:00:27	93.2	51	36.7	39.2	38.8
22/03/2002	17:00:47	93.2	51	36.5	37.1	37.4

APPENDIX A

Table A.7 Temperature Results on Point 5

Date	Clock	D020	D021	D022	D023	D024
22/03/2002	16:28:07	29.1	29.3	29.5	29.6	29.5
22/03/2002	16:28:27	29.1	29.3	29.4	29.5	29.5
22/03/2002	16:28:47	30.1	29.6	29.6	29.8	29.7
22/03/2002	16:29:07	33.3	31.1	29.8	29.8	29.8
22/03/2002	16:29:27	34.5	32.2	30.7	30.2	30
22/03/2002	16:29:47	36.1	33.5	31.2	30.6	30.1
22/03/2002	16:30:07	101.9	94.2	63.3	37	35
22/03/2002	16:30:27	92.7	77.7	49.2	36.8	35.4
22/03/2002	16:30:47	75.7	61.2	41.2	35	34.4
22/03/2002	16:31:07	61.2	50.7	37.4	33.4	32.9
22/03/2002	16:31:27	57.1	47	36.9	32.8	32.5
22/03/2002	16:31:47	55.6	45.7	35.3	31.9	32.2
22/03/2002	16:32:07	53.4	40	33.8	32.4	32.5
22/03/2002	16:32:27	53.2	39.5	33.2	32.3	32.3
22/03/2002	16:32:47	53.2	38.5	32.5	31.7	31.5
22/03/2002	16:33:07	53.5	37.3	32.3	31.2	31.1
22/03/2002	16:33:27	53.5	38.1	32.1	31.1	31
22/03/2002	16:33:47	55.6	40.5	31.8	31.1	31
22/03/2002	16:34:07	106.9	75.1	36.6	33.8	33.1
22/03/2002	16:34:27	106.8	74.7	37.2	33.5	32.8
22/03/2002	16:34:47	81.2	59.8	35.7	32.7	32.2
22/03/2002	16:35:07	69.1	52	35.1	32.6	32
22/03/2002	16:35:27	66.1	48.8	33.9	32.2	31.7
22/03/2002	16:35:47	66.5	46.3	33.2	31.9	31.5
22/03/2002	16:36:07	70.1	45.6	33.2	31.8	31.4
22/03/2002	16:36:27	152.6	102.7	40.3	35.2	33.7
22/03/2002	16:36:47	123.5	80.8	38.8	35.1	33.6
22/03/2002	16:37:07	100.3	64.7	36.7	34.3	33.5
22/03/2002	16:37:27	83.5	55.1	35.1	33.4	32.7
22/03/2002	16:37:47	73.4	48.6	33.9	32.7	32.1
22/03/2002	16:38:07	71.4	43.7	33.2	32.4	32
22/03/2002	16:38:27	78.2	42.5	34.3	32.6	32.2
22/03/2002	16:38:47	83.7	43.2	34.2	32.5	32.1
22/03/2002	16:39:07	88.3	46.1	34.9	32.9	32.3
22/03/2002	16:39:27	98	52.9	35.8	33.5	32.7
22/03/2002	16:39:47	112.6	58	36.8	34.1	33.1

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22/03/2002	16:40:07	126.6	64.3	37.1	34.5	33.4
22/03/2002	16:40:27	136	69	38	34.8	33.7
22/03/2002	16:40:47	150	68.2	37	34.1	33.6
22/03/2002	16:41:07	162.5	67.7	38.3	34.5	33.5
22/03/2002	16:41:27	168.9	67	39.1	35.4	34.1
22/03/2002	16:41:47	177.4	64	40.1	36.5	35
22/03/2002	16:42:07	188	68.6	41	36.9	35.2
22/03/2002	16:42:27	198	75.2	41.8	37.8	36.1
22/03/2002	16:42:47	211.6	80.9	42.3	38	36.6
22/03/2002	16:43:07	216.8	87	43.6	38.2	36.6
22/03/2002	16:43:27	216.8	99	44.4	39.1	37.2
22/03/2002	16:43:47	230.8	114	45.7	40.4	38
22/03/2002	16:44:07	250.3	107.3	46.9	41.5	39.1
22/03/2002	16:44:27	249.6	116.4	47.9	41.9	39.4
22/03/2002	16:44:47	266.9	156.4	49.2	42.3	39.7
22/03/2002	16:45:07	278.6	160.4	50.4	43.4	40.6
22/03/2002	16:45:27	281.6	160.8	52.2	44.4	41.1
22/03/2002	16:45:47	290.8	194.1	52.6	44.5	41.5
22/03/2002	16:46:07	310.3	194.1	55.9	46.1	43.1
22/03/2002	16:46:27	316.6	188.5	57	46.9	43.5
22/03/2002	16:46:47	324.9	190.3	58.5	48.2	43.7
22/03/2002	16:47:07	339.7	186.9	61.5	49.1	44.5
22/03/2002	16:47:27	345.6	193.1	63.5	50	45.7
22/03/2002	16:47:47	344.5	192	65.9	51.5	47.6
22/03/2002	16:48:07	348.7	193.4	66.4	52	47.9
22/03/2002	16:48:27	357.9	208.9	69.3	53.5	49.1
22/03/2002	16:48:47	365.6	208	71.5	54.8	50.2
22/03/2002	16:49:07	372.7	238.4	71.8	50.9	47.9
22/03/2002	16:49:27	376.6	242.9	71.2	54	49.6
22/03/2002	16:49:47	386	261.3	74.9	55.8	51
22/03/2002	16:50:07	380.2	307.6	81.5	57.5	53
22/03/2002	16:50:27	386.5	283.6	79.1	58.8	54
22/03/2002	16:50:47	386.8	298.6	80	60.2	54.6
22/03/2002	16:51:07	396.7	338.5	80	61.4	56
22/03/2002	16:51:27	412.2	335.4	84.3	64.5	59
22/03/2002	16:51:47	416.4	345.2	85.6	66.2	60.4
22/03/2002	16:52:07	435.4	361.4	87.6	69.3	63.2
22/03/2002	16:52:27	446.8	350.3	90.9	68.7	62.1
22/03/2002	16:52:47	453.8	398.6	99.2	69.2	62.7
22/03/2002	16:53:07	468	434.8	110.2	69.8	63.2

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22/03/2002	16:53:27	490.6	458.4	110.2	73.5	65.4
22/03/2002	16:53:47	498.6	452.5	112	76.3	70
22/03/2002	16:54:07	492.1	457.8	114.5	80.4	71.6
22/03/2002	16:54:27	494.4	463.5	116.5	78.7	71.6
22/03/2002	16:54:47	490.9	469.4	123.2	83.3	74.9
22/03/2002	16:55:07	489.8	459.9	123.2	85.5	75.9
22/03/2002	16:55:27	484.9	459.4	126.7	83.7	74.9
22/03/2002	16:55:47	477.1	440.4	124.5	84.3	76
22/03/2002	16:56:07	472.9	427.9	124.9	82	74.1
22/03/2002	16:56:27	467.7	462	124.8	81.5	74.9
22/03/2002	16:56:47	468.1	441.2	136	82.2	74.4
22/03/2002	16:57:07	450.1	424.9	146.2	74.3	71.7
22/03/2002	16:57:27	155.2	137.1	91	78.5	78
22/03/2002	16:57:48	108.1	93.8	77.9	67.9	70.6
22/03/2002	16:58:07	101.1	85.9	65.3	57.7	57.8
22/03/2002	16:58:27	90.8	76.3	63.5	54	52.2
22/03/2002	16:58:47	73	62.9	54.6	50.3	48.4
22/03/2002	16:59:07	78.9	59.4	52	46	44.2
22/03/2002	16:59:27	82.4	58	49.1	43.6	42.2
22/03/2002	16:59:47	82.3	56	47.9	42.4	41.3
22/03/2002	17:00:07	80.7	55.9	47.2	41.8	40.8
22/03/2002	17:00:27	78	55	46.8	41.5	41
22/03/2002	17:00:47	77	54.2	46.6	41.6	40.3

Table A.8 Temperature Results on Point 6

Date	Clock	D025	D026	D027	D028	D029
22/03/2002	16:28:07	29.7	29.7	29.6	29.4	29.5
22/03/2002	16:28:27	29.6	29.7	29.6	29.4	29.5
22/03/2002	16:28:47	29.8	29.8	29.7	29.6	29.6
22/03/2002	16:29:07	32.7	31.3	29.8	29.7	29.7
22/03/2002	16:29:27	33.1	31.9	30.2	29.7	29.6
22/03/2002	16:29:47	35	34.2	31.4	30.3	30
22/03/2002	16:30:07	105	102.9	80.2	37.8	34.4
22/03/2002	16:30:27	94.9	82.7	55.7	36.4	34.9
22/03/2002	16:30:47	77.2	62.7	44.1	34.3	33.6
22/03/2002	16:31:07	62.2	54	38.1	32.5	32.1
22/03/2002	16:31:27	54	38.8	35.5	32.7	32.5
22/03/2002	16:31:47	47.7	32.8	33.7	32.4	32.3
22/03/2002	16:32:07	48.1	39.6	34.3	31.7	31.5
22/03/2002	16:32:27	49.3	42.6	33.5	31.5	31.5
22/03/2002	16:32:47	49.7	43.4	32.8	31.1	30.8
22/03/2002	16:33:07	50.2	43.9	33.6	30.8	30.7
22/03/2002	16:33:27	50.7	45.5	32.8	31	30.9
22/03/2002	16:33:47	53.2	47.8	32.1	30.8	30.7
22/03/2002	16:34:07	104.3	85.7	43	32	31.8
22/03/2002	16:34:27	109.3	93.5	39.9	32.5	32
22/03/2002	16:34:47	83.7	71	36.5	32	31.6
22/03/2002	16:35:07	69.7	60.1	34.5	31.8	31.5
22/03/2002	16:35:27	65.1	57.5	33.3	31.5	31.3
22/03/2002	16:35:47	64.3	57.5	32.5	31.2	31.1
22/03/2002	16:36:07	67.4	58.9	32.2	31.2	31.1
22/03/2002	16:36:27	141.8	122.1	46.5	35	32.8
22/03/2002	16:36:47	122.1	95.5	42.1	34.6	33.3
22/03/2002	16:37:07	98.7	77.8	37.2	33.5	32.9
22/03/2002	16:37:27	83.5	64.3	34.7	32.8	32.6
22/03/2002	16:37:47	73.3	56.5	33.6	32.2	32.1
22/03/2002	16:38:07	69	56.1	33.4	31.8	31.7
22/03/2002	16:38:27	72	56.1	33.5	31.9	31.8
22/03/2002	16:38:47	78	59.3	33.7	32.1	31.8
22/03/2002	16:39:07	82.3	65.8	33.9	32.2	31.9
22/03/2002	16:39:27	90.8	78.1	34.4	32.4	32.1
22/03/2002	16:39:47	103.6	86.8	35	32.9	32.5
22/03/2002	16:40:07	116.8	97.4	35.1	33.1	32.8

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22/03/2002	16:40:27	126.1	105.4	35.5	33.2	33
22/03/2002	16:40:47	134.2	116.2	33.4	33.4	33.2
22/03/2002	16:41:07	144.3	124.9	32.7	33.5	33.4
22/03/2002	16:41:27	152.6	130.2	35.2	34.2	33.9
22/03/2002	16:41:47	159.7	133.3	36.4	34.7	34.5
22/03/2002	16:42:07	169.3	141.4	36.9	35.3	34.5
22/03/2002	16:42:27	179.4	149.6	37.9	35.7	34.7
22/03/2002	16:42:47	190.5	156.9	37.3	36	35.1
22/03/2002	16:43:07	196.1	162.7	37.9	35.9	35.5
22/03/2002	16:43:27	200	170.6	38.9	36.5	35.9
22/03/2002	16:43:47	208.8	179.3	41.6	37.8	36.5
22/03/2002	16:44:07	222.8	191.1	42.4	38.2	37
22/03/2002	16:44:27	227.7	200.4	42.8	38.8	37.6
22/03/2002	16:44:47	241.5	218.7	44.4	39	37.6
22/03/2002	16:45:07	252.8	224.7	44.9	39.1	38.3
22/03/2002	16:45:27	255.1	220.6	47	39.4	38.4
22/03/2002	16:45:47	268.5	244.2	46	39.8	38.8
22/03/2002	16:46:07	281.7	245.5	47.8	40.4	39.6
22/03/2002	16:46:27	282.9	259.6	48.3	40.3	39.9
22/03/2002	16:46:47	291.9	264.5	49.9	39.6	39.8
22/03/2002	16:47:07	295.5	271.7	46.7	41.1	40.9
22/03/2002	16:47:27	301.7	281.5	50.7	43.3	43
22/03/2002	16:47:47	301.5	272.9	52.3	45.4	44.7
22/03/2002	16:48:07	299.8	283.4	56.6	46.9	45.9
22/03/2002	16:48:27	308.4	297.8	60	48.7	47.6
22/03/2002	16:48:47	314	302.1	61	48.9	47.7
22/03/2002	16:49:07	324.5	313.6	54.7	48.4	47.2
22/03/2002	16:49:27	326.8	321	58.4	49.5	48.1
22/03/2002	16:49:47	337.7	329.4	61.3	50.4	48.1
22/03/2002	16:50:07	333.1	305.6	77.5	53.7	49.5
22/03/2002	16:50:27	340.3	318	77.4	51.1	48.4
22/03/2002	16:50:47	341.4	331.3	75.5	51	49.1
22/03/2002	16:51:07	346	343.6	75.7	53.5	51.8
22/03/2002	16:51:27	359.1	356.2	78.7	56.7	54.1
22/03/2002	16:51:47	362.2	361.9	74.1	57.1	55
22/03/2002	16:52:07	375.1	378	79.3	57.8	56.5
22/03/2002	16:52:27	384.2	387.8	80.1	58.7	56.5
22/03/2002	16:52:47	397.7	398.8	124.3	60	57
22/03/2002	16:53:07	400.9	407.6	190.3	55.3	55
22/03/2002	16:53:27	417.7	424.6	175.8	57.1	56.9
22/03/2002	16:53:47	414	425.9	159.4	63.2	61.2

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22/03/2002	16:54:07	421.8	432.5	149	64.2	61.5
22/03/2002	16:54:27	421.7	429	162	65.4	61.9
22/03/2002	16:54:47	417.3	428.4	190.1	67.9	64.2
22/03/2002	16:55:07	421.1	430.3	191	68.9	66.1
22/03/2002	16:55:27	413.3	425.7	212.7	68	65.9
22/03/2002	16:55:47	407.8	415.9	218.1	68.9	66.1
22/03/2002	16:56:07	401.9	414.5	216.4	69.9	65.7
22/03/2002	16:56:27	401.9	414.1	212.3	71.2	66.8
22/03/2002	16:56:47	404.5	410.8	228	71.8	67.5
22/03/2002	16:57:07	384.8	391.8	263.7	61.5	60.3
22/03/2002	16:57:27	164.9	135.6	105.1	65.8	66.2
22/03/2002	16:57:48	113.5	91.5	77.2	57.9	52.9
22/03/2002	16:58:07	101.7	81.9	65.5	52	48.3
22/03/2002	16:58:27	91.4	68	57	46.2	44
22/03/2002	16:58:47	71.9	56.2	50.5	43.1	42.1
22/03/2002	16:59:07	82.1	58.3	47.9	40.8	39.8
22/03/2002	16:59:27	86	57.9	46.5	41	40.5
22/03/2002	16:59:47	89.3	58	44.1	39	39.9
22/03/2002	17:00:07	91	57.7	42.8	39.8	39.9
22/03/2002	17:00:27	93.5	56.2	37.3	39.1	39.5
22/03/2002	17:00:47	92.2	55.7	40.4	38.8	39.6

Table A.9 Temperature Results on Point 7 and Point 8

Date	Clock	D030	D031	D032	D033	D034	D035
22/03/2002	16:28:07	29	29	29	28.9	28.9	29
22/03/2002	16:28:27	29	29	29	28.9	29	28.9
22/03/2002	16:28:47	30.3	29.1	29	28.9	29	29
22/03/2002	16:29:07	30.1	29.2	29.1	28.9	28.9	28.9
22/03/2002	16:29:27	30.6	29.2	29	29	29	28.9
22/03/2002	16:29:47	30.6	29.2	29.1	29.3	29	28.9
22/03/2002	16:30:07	53.6	29.7	29.5	29.6	29.2	29.1
22/03/2002	16:30:27	55.5	30.5	29.8	33.3	30.8	29.4
22/03/2002	16:30:47	49.9	31	30	32.4	30.3	29.6
22/03/2002	16:31:07	42.8	30.6	30	30.6	30.3	29.7
22/03/2002	16:31:27	41.1	30.6	29.9	30.1	30	29.8
22/03/2002	16:31:47	40.6	31.6	29.8	31.4	32.1	29.7
22/03/2002	16:32:07	39.3	31.9	29.8	32.2	32.6	29.8
22/03/2002	16:32:27	39.4	31.8	30	32.1	32.1	30
22/03/2002	16:32:47	39.6	31.4	30	32.3	31.5	30
22/03/2002	16:33:07	39.3	31.8	30	32.5	31.2	30
22/03/2002	16:33:27	36.8	31.2	29.9	32.2	31.1	30
22/03/2002	16:33:47	35.4	30.7	29.8	31.8	30.7	30
22/03/2002	16:34:07	34.4	30.3	29.9	30.8	30.1	29.8
22/03/2002	16:34:27	47.8	30.2	30	30	29.6	29.5
22/03/2002	16:34:47	43.9	30.3	29.8	30.1	30.1	29.6
22/03/2002	16:35:07	36.4	30	29.6	29.6	29.6	29.5
22/03/2002	16:35:27	33.3	29.9	29.5	29.4	29.4	29.3
22/03/2002	16:35:47	34.2	29.7	29.4	29.1	29.2	29.2
22/03/2002	16:36:07	37.3	29.8	29.3	29	29.1	29.2
22/03/2002	16:36:27	74	30.2	29.8	33.3	31	29.3
22/03/2002	16:36:47	66.9	32.5	29.9	39.4	30.9	29.6
22/03/2002	16:37:07	61	32.5	29.9	38.8	31.5	29.6
22/03/2002	16:37:27	55.1	31.7	29.8	37.6	31.6	29.7
22/03/2002	16:37:47	50.7	31.2	29.8	36.2	31.4	29.8
22/03/2002	16:38:07	48.6	31.2	29.9	36.3	30.9	29.6
22/03/2002	16:38:27	48.2	31.8	29.9	35.1	30.9	29.6
22/03/2002	16:38:47	45.3	31.4	30	34.1	30.8	29.6
22/03/2002	16:39:07	40.9	31	30	31.9	30.2	29.6
22/03/2002	16:39:27	37.5	30.6	29.9	30.1	29.5	29.4
22/03/2002	16:39:47	42.6	30.5	29.9	29.5	29.3	29.2
22/03/2002	16:40:07	40	30.6	30.1	29.3	29.4	29.4

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22/03/2002	16:40:27	48.5	30.2	29.9	29.1	29.2	29.3
22/03/2002	16:40:47	71	30.3	29.9	31.2	29.4	29.3
22/03/2002	16:41:07	84.7	30.8	30	41.3	29.8	29.3
22/03/2002	16:41:27	90.3	31.4	30.3	42.7	30.3	29.5
22/03/2002	16:41:47	95.1	31.7	30.5	42.7	30.8	29.6
22/03/2002	16:42:07	100.7	31.9	30.7	42.9	30.9	29.6
22/03/2002	16:42:27	106.3	32.4	30.9	43.3	31.6	29.8
22/03/2002	16:42:47	114.2	33	31.3	46.7	31.7	30.2
22/03/2002	16:43:07	117.7	35	31.5	49.1	33.5	30.4
22/03/2002	16:43:27	118.8	36.2	32	49.1	33.9	31.4
22/03/2002	16:43:47	124.5	36.4	32.3	49.1	33.8	31.7
22/03/2002	16:44:07	135.3	36.7	32.6	54	33.7	31.5
22/03/2002	16:44:27	138.3	36.8	32.7	54.4	34.1	31.3
22/03/2002	16:44:47	136.5	36.7	32.7	52.5	34.9	31.8
22/03/2002	16:45:07	147.5	37.6	34	50.3	35	32.5
22/03/2002	16:45:27	149.8	38.6	33.6	53.3	34.3	32.2
22/03/2002	16:45:47	159.4	40.6	34.3	56.7	36.2	33.4
22/03/2002	16:46:07	164.8	39.2	34.6	53.7	36.4	33.7
22/03/2002	16:46:27	174	40.5	34.2	65.1	37	33.5
22/03/2002	16:46:47	176.6	42	34.4	71.8	37.2	33.7
22/03/2002	16:47:07	190.7	44.8	34.3	82.1	38.3	33.9
22/03/2002	16:47:27	198	43.8	34.6	91.2	39.5	33.6
22/03/2002	16:47:47	204.8	44.1	34.7	96.7	41.6	33.1
22/03/2002	16:48:07	209.5	47.1	35.1	99.8	45.7	33
22/03/2002	16:48:27	208.3	50.4	36.2	103.2	49.9	33.3
22/03/2002	16:48:47	213.2	49.1	36.8	103.9	47.9	33.7
22/03/2002	16:49:07	228.6	50.4	37.7	106.8	48	34
22/03/2002	16:49:27	231.9	52.4	37.1	108.4	50.6	34.1
22/03/2002	16:49:47	237	52.1	38	103.9	50.3	35.1
22/03/2002	16:50:07	220.5	51.4	39	93.5	48.9	37.3
22/03/2002	16:50:27	221	53.5	40.8	88.2	47.3	39
22/03/2002	16:50:47	231.5	57.4	39.7	95.1	49.8	39.9
22/03/2002	16:51:07	251.7	59	41.9	101.7	50.5	40.9
22/03/2002	16:51:27	258.2	61.4	41.7	112.1	53.7	40
22/03/2002	16:51:47	275.6	64.7	42.3	122.2	54.6	39.3
22/03/2002	16:52:07	286.6	66.6	42.7	129.3	58.1	38.1
22/03/2002	16:52:27	280.8	63.7	42.7	135.9	59.5	37.9
22/03/2002	16:52:47	286.5	59.8	40.6	137.7	56.1	37.1
22/03/2002	16:53:07	297.4	61.6	40.1	139.1	55.7	37.3
22/03/2002	16:53:27	313.2	65.7	41.3	147.1	67.1	36.8
22/03/2002	16:53:47	325.5	77.1	43.3	153.9	74.9	37.6

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22/03/2002	16:54:07	330.6	80.1	44.7	157.3	78.2	38.3
22/03/2002	16:54:27	329.3	80.8	44.6	161	79.8	38
22/03/2002	16:54:47	342.7	80.1	45.7	164.5	76.8	38.7
22/03/2002	16:55:07	342.7	83.3	47.5	159.9	76.9	39.6
22/03/2002	16:55:27	353.8	81.4	49	159.7	73.1	39.9
22/03/2002	16:55:47	350.5	85.2	49.1	161.1	75.1	39.9
22/03/2002	16:56:07	335.5	83.9	48.6	160.6	74.6	40.4
22/03/2002	16:56:27	346.2	81.8	48.3	164.6	73.8	40.3
22/03/2002	16:56:47	340.4	78.8	48.6	163.4	73.9	40.2
22/03/2002	16:57:07	306.4	78.9	46.6	148.9	66.5	42.6
22/03/2002	16:57:27	203	72.1	42.7	126.6	63.6	41.4
22/03/2002	16:57:48	133	59.3	40.8	101.1	54.9	40.2
22/03/2002	16:58:07	98	51.5	38.7	79.6	50	39.6
22/03/2002	16:58:27	84.3	43.8	37.1	63.3	43.8	38.2
22/03/2002	16:58:47	66.8	39.9	35.7	53	39.5	36.3
22/03/2002	16:59:07	60.5	38	35.1	45.8	37	34.6
22/03/2002	16:59:27	60.2	37.9	34.3	44.7	35.8	33.7
22/03/2002	16:59:47	62.4	37.8	33.7	43.1	35.3	33.5
22/03/2002	17:00:07	61.5	36.9	34.1	42.9	34.4	33
22/03/2002	17:00:27	61	36.9	33.8	43.3	34.9	33.1
22/03/2002	17:00:47	59.8	37.3	33.9	44.8	35.1	32.9

Table A.10 Temperature Results on Point 9

Date	Clock	D036	D037	D038
22/03/2002	16:28:07	28.9	28.9	28.9
22/03/2002	16:28:27	28.9	28.9	29
22/03/2002	16:28:47	28.9	28.9	29
22/03/2002	16:29:07	28.9	28.9	28.9
22/03/2002	16:29:27	28.9	29	28.9
22/03/2002	16:29:47	29	29	29
22/03/2002	16:30:07	29	29	29
22/03/2002	16:30:27	29.9	29.3	29.1
22/03/2002	16:30:47	30.1	29.3	29.1
22/03/2002	16:31:07	29.5	29.5	29.4
22/03/2002	16:31:27	29.5	29.4	29.4
22/03/2002	16:31:47	30.5	29.8	29.5
22/03/2002	16:32:07	31.6	30.3	29.6
22/03/2002	16:32:27	31.6	30.5	29.9
22/03/2002	16:32:47	31.4	30.6	30.1
22/03/2002	16:33:07	32.2	30.6	30.1
22/03/2002	16:33:27	31.3	30.2	29.9
22/03/2002	16:33:47	29.8	29.9	29.7
22/03/2002	16:34:07	29.2	29.5	29.6
22/03/2002	16:34:27	29	29.2	29.3
22/03/2002	16:34:47	29	29.1	29.2
22/03/2002	16:35:07	28.9	29.1	29.3
22/03/2002	16:35:27	28.9	29	29
22/03/2002	16:35:47	28.9	28.9	29
22/03/2002	16:36:07	28.9	28.9	28.9
22/03/2002	16:36:27	28.9	29	29
22/03/2002	16:36:47	34.9	30.8	29.6
22/03/2002	16:37:07	36.6	30.9	29.7
22/03/2002	16:37:27	35.9	30.6	29.8
22/03/2002	16:37:47	34.8	30.2	29.5
22/03/2002	16:38:07	34.2	30.8	29.5
22/03/2002	16:38:27	33.9	30.8	29.4
22/03/2002	16:38:47	31.4	30	29.6
22/03/2002	16:39:07	29.8	29.4	29.3
22/03/2002	16:39:27	29.1	29	28.9
22/03/2002	16:39:47	28.9	28.9	28.9
22/03/2002	16:40:07	28.8	29	28.9

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22/03/2002	16:40:27	28.9	28.9	28.9
22/03/2002	16:40:47	29.1	29.1	29
22/03/2002	16:41:07	34.3	31.4	29.7
22/03/2002	16:41:27	37.4	31.6	29.7
22/03/2002	16:41:47	37.8	31.5	29.9
22/03/2002	16:42:07	37.6	32.1	29.7
22/03/2002	16:42:27	37.9	31.8	29.9
22/03/2002	16:42:47	39.6	33.1	29.9
22/03/2002	16:43:07	42.1	32.9	30.1
22/03/2002	16:43:27	44.3	32.3	30.1
22/03/2002	16:43:47	39.3	30.8	29.6
22/03/2002	16:44:07	45.3	36.3	31
22/03/2002	16:44:27	47.3	35.7	30.5
22/03/2002	16:44:47	39.7	33.2	30.3
22/03/2002	16:45:07	36.8	31.5	30.3
22/03/2002	16:45:27	40.9	33.6	31.8
22/03/2002	16:45:47	45.6	35.2	33.4
22/03/2002	16:46:07	38.6	32.5	31.7
22/03/2002	16:46:27	48.4	37.3	33
22/03/2002	16:46:47	55.2	41.1	32.6
22/03/2002	16:47:07	63.8	42.7	32
22/03/2002	16:47:27	70.5	49.2	31.7
22/03/2002	16:47:47	76.5	51.8	31.8
22/03/2002	16:48:07	81.2	55.9	31.4
22/03/2002	16:48:27	85.6	59.5	31.7
22/03/2002	16:48:47	85.8	60.2	31.5
22/03/2002	16:49:07	87.3	59.2	33.5
22/03/2002	16:49:27	89.4	63.6	34
22/03/2002	16:49:47	88.3	57.7	35.8
22/03/2002	16:50:07	64.7	44.3	37.3
22/03/2002	16:50:27	67.9	41.7	37.4
22/03/2002	16:50:47	76.9	48.5	39
22/03/2002	16:51:07	83.3	58.3	36.9
22/03/2002	16:51:27	89.6	61.8	36.4
22/03/2002	16:51:47	97.6	68.4	36.7
22/03/2002	16:52:07	109.5	73.9	33.9
22/03/2002	16:52:27	110.5	71.8	33.8
22/03/2002	16:52:47	108.7	67.6	32.7
22/03/2002	16:53:07	108.4	68.9	34.3
22/03/2002	16:53:27	116.2	78.5	34.5
22/03/2002	16:53:47	120.4	93.1	35.8

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22/03/2002	16:54:07	125.6	90.7	36.2
22/03/2002	16:54:27	130.6	90.3	37.3
22/03/2002	16:54:47	129.3	86.3	39
22/03/2002	16:55:07	128.9	82.5	40
22/03/2002	16:55:27	126.5	87	41.9
22/03/2002	16:55:47	128.9	82.7	42.4
22/03/2002	16:56:07	128.7	87.5	41.1
22/03/2002	16:56:27	131.6	96.9	39.4
22/03/2002	16:56:47	131.2	81.6	37.7
22/03/2002	16:57:07	125.2	77.9	41.6
22/03/2002	16:57:27	114.6	65.1	41.2
22/03/2002	16:57:48	93.9	54.3	39.5
22/03/2002	16:58:07	62	46.1	37.7
22/03/2002	16:58:27	41.5	38.5	35.3
22/03/2002	16:58:47	34.6	35.7	34.2
22/03/2002	16:59:07	34.8	34.1	33.4
22/03/2002	16:59:27	37.3	34	33.3
22/03/2002	16:59:47	38.8	33.4	32.7
22/03/2002	17:00:07	39.9	34.2	33.1
22/03/2002	17:00:27	41.9	35.1	33.2
22/03/2002	17:00:47	42	35.5	32.9

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A.3 Gas Concentration Results for CF001, Normal Configuration

Table A.11 Gas Concentrations Measurement Results on Point 1

Date	Clock	CO ₂ (ppm)	CO (ppm)	H ₂ O (mg/m ³)
22/03/02	16:21:23	748.669983	1.285	20014
22/03/02	16:24:44	769.549988	1.2698	20204
22/03/02	16:33:24	745.419983	1.4728	20303
22/03/02	16:44:39	840.799988	1.8675	20090
22/03/02	16:51:27	1242	5.0969	20540
22/03/02	16:57:39	910.02002	4.4889	19927
22/03/02	17:04:02	735.539978	1.7664	19965
22/03/02	17:10:30	729.820007	2.1905	20875
22/03/02	17:16:42	790.150024	2.2019	22264

Table A.12 Gas Concentrations Measurement Results on Point 7

Date	Clock	CO ₂ (ppm)	CO (ppm)	H ₂ O (mg/m ³)
22/03/2002	16:26:19	769.549988	1.2698	20204
22/03/2002	16:34:58	725.630005	1.4578	20158
22/03/2002	16:46:13	777.119995	1.219	19886
22/03/2002	16:52:27	1908.099976	9.1571	20449
22/03/2002	16:58:40	896.330017	4.9973	20095
22/03/2002	17:05:02	727.25	1.8774	20151
22/03/2002	17:11:35	723.98999	2.6829	23861
22/03/2002	17:17:48	740.099976	1.989	20902

Table A.13 Gas Concentrations Measurement Results on Point 9

Date	Clock	CO ₂ (ppm)	CO (ppm)	H ₂ O (mg/m ³)
22/03/2002	16:35:55	723.359985	1.277	20233
22/03/2002	16:47:10	811.169983	1.4301	19991
22/03/2002	16:53:33	1878	8.6004	20533
22/03/2002	17:00:00	841.859985	3.9574	20450
22/03/2002	17:06:03	721.179993	1.7505	19954
22/03/2002	17:12:36	717.929993	1.9211	20749
22/03/2002	17:18:48	722.02002	1.784	20065

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Table A.14 Gas Concentrations Measurement Results on Point 6

Date	Clock	CO ₂ (ppm)	CO (ppm)	H ₂ O (mg/m ³)
22/03/2002	16:36:55	750.27002	1.8416	20188
22/03/2002	16:48:10	947.559998	1.9026	20313
22/03/2002	16:54:33	1296	5.2331	20223
22/03/2002	17:01:01	826.940002	1.7188	19556
22/03/2002	17:07:08	721.919983	1.8355	20569
22/03/2002	17:13:36	717.580017	2.0518	20884
22/03/2002	17:20:04	721.349976	2.1107	20956

Table A.15 Gas Concentrations Measurement Results on Point 3

Date	Clock	CO ₂ (ppm)	CO (ppm)	H ₂ O (mg/m ³)
22/03/2002	16:49:26	1077.800049	2.3104	19989
22/03/2002	16:55:39	1154.300049	4.3445	20230
22/03/2002	17:02:01	775.390015	2.7817	20406
22/03/2002	17:08:09	720.840027	1.7442	19702
22/03/2002	17:14:36	716.309998	2.1427	20742

Table A.16 Gas Concentrations Measurement Results on Point 4

Date	Clock	CO ₂ (ppm)	CO (ppm)	H ₂ O (mg/m ³)
22/03/2002	16:50:26	1013.799988	2.2483	20244
22/03/2002	16:56:39	1292.199951	7.4809	20557
22/03/2002	17:03:02	742.179993	2.1163	20302
22/03/2002	17:09:24	744.700012	2.3678	20792
22/03/2002	17:15:37	717.960022	2.1258	20535

A.4 Temperature Results for CF002, White-Block Configuration

Figure A.2 Locations of Measuring Points for CF002

Table A.17 Temperature Results on Point 1

Date	Clock	D000	D001	D002	D003	D004
15/04/2002	15:10:05	28.9	29.3	29.4	29.5	29.6
15/04/2002	15:10:21	29	29.3	29.4	29.5	29.6
15/04/2002	15:10:36	29	29.3	29.5	29.5	29.7
15/04/2002	15:10:51	29	29.3	29.4	29.5	29.6
15/04/2002	15:11:05	28.9	29.2	29.4	29.5	29.6
15/04/2002	15:11:20	29	29.3	29.4	29.4	29.6
15/04/2002	15:11:36	29	29.3	29.4	29.5	29.7
15/04/2002	15:11:50	29.1	29.4	29.5	29.6	29.8
15/04/2002	15:12:06	29.1	29.4	29.5	29.6	29.7
15/04/2002	15:12:20	29	29.3	29.4	29.5	29.6
15/04/2002	15:12:36	28.9	29.2	29.4	29.4	29.6
15/04/2002	15:12:51	30	30.1	30.2	30.3	30.5
15/04/2002	15:13:05	46	31.7	31.3	31.2	31.3
15/04/2002	15:13:20	57.2	34.4	32.9	32.6	32.5
15/04/2002	15:13:35	44	36.7	35.6	34.9	34.7
15/04/2002	15:13:51	36.6	35.3	34.7	34.3	34
15/04/2002	15:14:05	35.5	33.7	33.6	33.7	33.6
15/04/2002	15:14:20	40.5	34.7	33.2	33	32.7

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15/04/2002	15:14:36	41.9	33.7	32.7	32.5	32.3
15/04/2002	15:14:50	36.5	32.4	32.3	33.5	33.8
15/04/2002	15:15:06	34.8	33.6	33.2	33.2	33.1
15/04/2002	15:15:20	33.2	33.3	33.1	32.9	32.9
15/04/2002	15:15:35	35.1	32.5	32.4	32.4	32.5
15/04/2002	15:15:50	45.1	33.2	32.4	32.4	32.4
15/04/2002	15:16:06	46.7	33.5	31.9	31.9	32
15/04/2002	15:16:21	38	33.5	32.7	32.2	32.1
15/04/2002	15:16:35	34.8	33.3	32.8	32.6	32.5
15/04/2002	15:16:51	39	33.4	32.8	32.8	32.9
15/04/2002	15:17:06	34.5	33.2	33.4	33.4	33.7
15/04/2002	15:17:20	34.7	33	33.5	33.6	33.7
15/04/2002	15:17:35	33.1	33.2	33.5	33.6	33.6
15/04/2002	15:17:50	36	34.6	33.8	33.1	33
15/04/2002	15:18:05	38	34.9	33.7	32.6	32.5
15/04/2002	15:18:20	38.1	34.2	33.7	33.1	33
15/04/2002	15:18:36	34.6	33.6	33.5	33.2	33.3
15/04/2002	15:18:50	33.9	33.5	33.6	33.4	33.5
15/04/2002	15:19:05	33.6	33.7	33.9	33.8	34.1
15/04/2002	15:19:21	34.8	33.7	34	34	34.1
15/04/2002	15:19:35	40.1	34	34.3	34.3	34.3
15/04/2002	15:19:50	45.4	34.7	34	33.3	33.2
15/04/2002	15:20:05	37.8	34.8	34.7	34.4	34.3
15/04/2002	15:20:20	35.8	36.5	35.6	34.9	34.9
15/04/2002	15:20:36	34.7	35.8	35.7	35.5	35.5
15/04/2002	15:20:51	34.7	35.4	35.5	35.6	36
15/04/2002	15:21:06	34.7	35.2	35.5	35.8	36.5
15/04/2002	15:21:20	36.1	36.9	37.5	36.9	36.7
15/04/2002	15:21:36	37	39.3	38.8	37.7	37.6
15/04/2002	15:21:51	37.2	39.4	39.3	38.7	38.7
15/04/2002	15:22:05	37.9	39.7	40.1	39.6	39.7
15/04/2002	15:22:20	47.1	40.9	41.2	40.7	40.4
15/04/2002	15:22:35	51.5	40.9	41.5	40.9	41.1
15/04/2002	15:22:51	45.4	43.4	43.5	42.8	42.8
15/04/2002	15:23:06	44	44.7	45.1	44.4	44.1
15/04/2002	15:23:21	58	47	47.5	46.6	45.8
15/04/2002	15:23:35	91.1	51	49.8	48.3	46.3
15/04/2002	15:23:51	122.7	68.5	52.3	47.7	44.8
15/04/2002	15:24:06	85.1	58.9	52.2	50	47.9
15/04/2002	15:24:20	118	57	55.8	51.9	49.8
15/04/2002	15:24:36	150.4	75.7	57.8	52.9	50

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15/04/2002	15:24:51	174.3	81	53.2	47.4	45.9
15/04/2002	15:25:06	159.2	77.8	56.1	48.3	45.1
15/04/2002	15:25:20	156	73.9	62.2	55.7	52.7
15/04/2002	15:25:35	138.8	70.6	65.4	60	56.9
15/04/2002	15:25:51	103	69.9	69	65.2	61.8
15/04/2002	15:26:05	76.7	69	69.6	67.5	64.2
15/04/2002	15:26:21	161.9	81.3	69.1	66.7	62.4
15/04/2002	15:26:35	215.2	98	67.1	61.2	58.7
15/04/2002	15:26:50	200.3	85.7	66.4	55.3	52.9
15/04/2002	15:27:05	221.1	96.8	72.5	62.6	60.4
15/04/2002	15:27:21	222.5	103.3	69.4	59.4	57.6
15/04/2002	15:27:35	130	96.2	77	67.1	63.6
15/04/2002	15:27:50	103	80.9	76.1	71.1	68.5
15/04/2002	15:28:06	204.3	95.1	80.5	73.2	69.1
15/04/2002	15:28:20	237	105.4	76.1	72.1	67.8
15/04/2002	15:28:35	259.8	137.1	80.4	71.4	68.7
15/04/2002	15:28:50	289.7	151.4	74.6	69.5	65.3
15/04/2002	15:29:05	274.5	125	76	72	66.6
15/04/2002	15:29:21	273.4	146.9	94.9	78.7	74.4
15/04/2002	15:29:35	292.3	146.6	96.8	84	78.7
15/04/2002	15:29:50	331.8	173.9	95.1	82.4	76.2
15/04/2002	15:30:05	347.5	182.1	89.1	77.4	71.9
15/04/2002	15:30:20	338.5	187.3	92.9	79.3	71.5
15/04/2002	15:30:35	356.5	187.8	90.9	78.4	73.6
15/04/2002	15:30:51	315.7	165.9	89.8	74.4	72.1
15/04/2002	15:31:05	367.5	186.2	106	79.6	73
15/04/2002	15:31:20	392.4	205.9	103.4	86.1	79.1
15/04/2002	15:31:35	393.6	217.9	107.2	88.7	81.9
15/04/2002	15:31:51	387.1	227.6	115.5	96.2	88.2
15/04/2002	15:32:05	403.9	236	111.1	97.4	90.7
15/04/2002	15:32:20	433.5	246	110.2	94.6	88.8
15/04/2002	15:32:35	423.4	253.2	118.8	95.8	88.8
15/04/2002	15:32:50	425.7	253	103.6	92.8	85.8
15/04/2002	15:33:05	457.8	255.4	102.2	92.2	86.8
15/04/2002	15:33:20	461.4	260.7	97.5	89	84.5
15/04/2002	15:33:35	430.3	262.7	112.6	90.8	81
15/04/2002	15:33:51	455.8	264.7	135.8	100.9	91.4
15/04/2002	15:34:06	492.9	281.1	133	103.4	94.9
15/04/2002	15:34:20	476.3	284.5	147.2	107.4	99.4
15/04/2002	15:34:35	488.2	287.8	130.9	109.7	104.7
15/04/2002	15:34:50	493.8	284.1	125.5	105.6	99.5

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15/04/2002	15:35:06	515.6	297.2	134.6	100.8	96.1
15/04/2002	15:35:20	511.2	305.6	136.8	102.9	99.1
15/04/2002	15:35:35	503.4	295	154.5	114.6	103.7
15/04/2002	15:35:50	537	313.4	165.7	116.3	110.8
15/04/2002	15:36:05	541.2	311.9	153.1	111.9	108
15/04/2002	15:36:20	522.9	306.7	149.4	115.6	108.8
15/04/2002	15:36:36	513.5	257.1	143.8	114.2	108.3
15/04/2002	15:36:51	503.5	267.3	132.7	110.1	104
15/04/2002	15:37:05	553.5	281.2	137.6	109.2	101.7
15/04/2002	15:37:21	585.4	324.7	149.7	113.7	106.8
15/04/2002	15:37:35	564.8	330.7	169.9	123	115.2
15/04/2002	15:37:50	580.2	335.2	167.8	131.2	118.4
15/04/2002	15:38:06	562.5	331.2	168.8	126.4	119.3
15/04/2002	15:38:20	572.6	335.6	150.1	124.2	119.8
15/04/2002	15:38:36	596.9	351.4	197	137.9	128.5
15/04/2002	15:38:51	604.5	363.1	192	138.6	129.1
15/04/2002	15:39:05	575.6	353.3	174.1	134.6	126.4
15/04/2002	15:39:20	591.9	364.5	181.2	123.7	117.3
15/04/2002	15:39:35	601.6	338.1	194.1	149.4	143.1
15/04/2002	15:39:50	626.4	363.3	216.7	163.2	146.7
15/04/2002	15:40:05	614.8	367.4	192.8	154.3	141.2
15/04/2002	15:40:21	598.2	359.6	196.3	149.8	135.4
15/04/2002	15:40:35	595.3	356.8	187.4	156.7	141.5
15/04/2002	15:40:50	580.7	347.2	185.1	152.6	143.2
15/04/2002	15:41:05	610.8	346.7	177.7	147.7	133.9
15/04/2002	15:41:20	577.1	370.6	178.7	144.9	130.8
15/04/2002	15:41:36	604.8	366.7	157.2	134	126.3
15/04/2002	15:41:50	595.8	378.5	159	127.7	122.5
15/04/2002	15:42:05	552.4	335.2	159.8	134	131.2
15/04/2002	15:42:21	492.5	288.4	172	134.7	121.4
15/04/2002	15:42:36	527	298	211.1	172.8	153.5
15/04/2002	15:42:50	555.4	340.1	186.3	158.6	147.8
15/04/2002	15:43:05	536.2	332.8	186.9	152.6	147.3
15/04/2002	15:43:20	513.9	326	176.4	133.8	133.2
15/04/2002	15:43:35	476.6	318.1	198.9	145.5	140.3
15/04/2002	15:43:50	507.1	335.9	186.2	140.1	134.6
15/04/2002	15:44:05	461.6	306.6	199.1	150.7	142.2
15/04/2002	15:44:21	438.6	308.4	191.1	145.5	140
15/04/2002	15:44:36	451.8	301.7	170.6	138.4	132.4
15/04/2002	15:44:51	410.6	267.5	151.2	123.7	123.1
15/04/2002	15:45:05	411.1	262.4	149.9	123.9	121.8

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15/04/2002	15:45:20	408.3	276.5	165.6	133.1	126.2
15/04/2002	15:45:36	379.7	264	150.9	124	119.2
15/04/2002	15:45:51	346.6	241.8	140.1	118.7	116.7
15/04/2002	15:46:05	319.6	203.2	131.8	114.6	112.1
15/04/2002	15:46:20	280.7	197.7	119.6	100	95.2
15/04/2002	15:46:35	232.9	184.9	117.6	94.2	87.2
15/04/2002	15:46:51	199.8	167.2	122.6	91.5	85.4
15/04/2002	15:47:05	185.3	153	119	90.1	82.7
15/04/2002	15:47:20	182.2	130.3	108	84.1	78.2
15/04/2002	15:47:35	188.3	150.7	102	83	76.5
15/04/2002	15:47:50	165.8	133.7	98.4	77.2	69.1
15/04/2002	15:48:05	138.9	114.8	93.1	76	68.8
15/04/2002	15:48:20	134.8	111.3	93.5	78	72.2
15/04/2002	15:48:35	134.1	111.8	94.8	76.2	68.2
15/04/2002	15:48:51	129.8	109.8	95.7	75.4	61.3
15/04/2002	15:49:05	121.3	105.1	89	69.5	58.2
15/04/2002	15:49:20	109.5	94.1	79.8	63.6	56
15/04/2002	15:49:35	106.7	87.4	76.2	62.4	56.6
15/04/2002	15:49:50	103.6	87.3	73.1	61.9	54.5
15/04/2002	15:50:05	88.6	74.4	66.9	58.5	53.8
15/04/2002	15:50:21	91.6	76.1	69.9	61.6	57.8
15/04/2002	15:50:35	96.5	78.6	68.2	60.5	58.4
15/04/2002	15:50:51	100	81.9	69.6	59.7	57.9

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Table A.18 Temperature Results on Point 2

Date	Clock	D005	D006	D007	D008	D009
15/04/2002	15:10:05	29.6	29.7	29.8	29.7	29.8
15/04/2002	15:10:21	29.6	29.8	29.8	29.8	29.9
15/04/2002	15:10:36	29.6	29.8	29.8	29.8	29.8
15/04/2002	15:10:51	29.6	29.7	29.8	29.8	29.8
15/04/2002	15:11:05	29.6	29.7	29.8	29.8	29.8
15/04/2002	15:11:20	29.6	29.7	29.8	29.8	29.8
15/04/2002	15:11:36	29.6	29.8	29.8	29.9	29.9
15/04/2002	15:11:50	29.7	29.9	29.9	29.9	30
15/04/2002	15:12:06	29.7	29.9	29.9	29.9	30
15/04/2002	15:12:20	29.6	29.7	29.8	29.9	29.9
15/04/2002	15:12:36	29.5	29.7	29.8	29.8	29.8
15/04/2002	15:12:51	30.3	30.1	30.2	30.3	30.4
15/04/2002	15:13:05	38.7	34.5	31.7	30.5	30.6
15/04/2002	15:13:20	47.4	38.8	33.3	32	32.3
15/04/2002	15:13:35	40.5	39.9	37	35.4	34.8
15/04/2002	15:13:51	35.7	36.4	34.8	33.7	33.3
15/04/2002	15:14:05	34.2	34.4	33.8	33.5	33.3
15/04/2002	15:14:20	36.8	34.3	32.7	32.4	32.3
15/04/2002	15:14:36	38.7	35.1	32.6	32.2	32
15/04/2002	15:14:50	35.2	32	31.7	32.4	32.5
15/04/2002	15:15:06	33.3	33	32.3	32.7	32.6
15/04/2002	15:15:20	33.4	32.8	32.5	32.7	32.6
15/04/2002	15:15:35	33.8	32.7	32	32.1	32.2
15/04/2002	15:15:50	42.4	38.2	32.5	31.9	31.9
15/04/2002	15:16:06	44.8	36.7	32.4	32.1	32
15/04/2002	15:16:21	36	33.5	32.1	32	32.2
15/04/2002	15:16:35	33.9	33.3	32.4	32.4	32.6
15/04/2002	15:16:51	34.8	33.7	33	33	33
15/04/2002	15:17:06	33.3	33.1	32.8	32.9	32.9
15/04/2002	15:17:20	34.9	33.8	33.1	32.9	32.9
15/04/2002	15:17:35	33.3	33	32.6	32.8	32.9
15/04/2002	15:17:50	35.4	34.6	32.3	32.6	32.5
15/04/2002	15:18:05	37.1	35.5	33.3	32.9	32.6
15/04/2002	15:18:20	36.6	35.2	33.7	33	33
15/04/2002	15:18:36	34	34	33.4	33.1	33.2
15/04/2002	15:18:50	33.4	33.9	33.7	33.5	33.6
15/04/2002	15:19:05	33.5	33.9	33.9	33.8	33.9

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15/04/2002	15:19:21	33.7	34.1	34	33.9	33.9
15/04/2002	15:19:35	36.9	35.9	34	34.1	34
15/04/2002	15:19:50	41.9	37.3	35.3	33.6	33
15/04/2002	15:20:05	36	35	34.5	34.3	34.1
15/04/2002	15:20:20	34.5	34.7	34.1	34	33.7
15/04/2002	15:20:36	34.1	34.1	34	34.4	34.1
15/04/2002	15:20:51	34.4	34	34.2	34.9	34.3
15/04/2002	15:21:06	34.6	33.9	33.9	34.9	35.2
15/04/2002	15:21:20	35.5	35	36	36.1	36
15/04/2002	15:21:36	37.9	39.5	38.2	37.6	37.2
15/04/2002	15:21:51	37.4	38.7	38.2	37.8	37.8
15/04/2002	15:22:05	38	39.2	38.5	38.4	38.4
15/04/2002	15:22:20	39.8	40.7	40.4	39.5	39.8
15/04/2002	15:22:35	39.6	41.9	42.2	40.9	41
15/04/2002	15:22:51	41	43.9	42.3	41.8	42.4
15/04/2002	15:23:06	42.4	44.1	43.1	42.6	41.7
15/04/2002	15:23:21	44.8	45.9	45.4	42.8	41.3
15/04/2002	15:23:35	64.2	62.1	52.5	44.9	43.3
15/04/2002	15:23:51	99.2	87.6	49.5	43.4	41.6
15/04/2002	15:24:06	79.7	76.6	52.9	47.6	45.7
15/04/2002	15:24:20	94.6	81	53.5	48.5	47.1
15/04/2002	15:24:36	129.8	105.5	51.9	46.4	44.1
15/04/2002	15:24:51	143	104.8	47.1	43.1	40.5
15/04/2002	15:25:06	122.2	86	54.1	45.4	42.5
15/04/2002	15:25:20	127.3	91.4	59.5	52.5	48.4
15/04/2002	15:25:35	97.3	75.8	65.2	59.4	54
15/04/2002	15:25:51	66.9	72.1	66.2	62.3	59.3
15/04/2002	15:26:05	58.9	67.6	66.5	60.9	58.2
15/04/2002	15:26:21	134.2	112.3	63.3	56.7	53.4
15/04/2002	15:26:35	165.7	142.7	57.1	51.3	48.9
15/04/2002	15:26:50	136	112.3	66.3	50.5	45.8
15/04/2002	15:27:05	176.8	145	66.7	53.5	51.6
15/04/2002	15:27:21	179.6	135.9	58.3	49.8	47.3
15/04/2002	15:27:35	100.8	104.2	67.2	56.5	55.6
15/04/2002	15:27:50	80	81.4	70.4	62.9	61.8
15/04/2002	15:28:06	155.6	130	70.2	62.8	58.7
15/04/2002	15:28:20	187.8	155.6	77.9	59.2	56.5
15/04/2002	15:28:35	210	178.7	78.2	56.6	53.5
15/04/2002	15:28:50	230.7	198	68	53.2	49.5
15/04/2002	15:29:05	210.9	165.1	80.4	61.6	58.4
15/04/2002	15:29:21	218.3	185.4	93.9	65.9	59.2

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15/04/2002	15:29:35	231.7	192.5	100.8	76.4	70.5
15/04/2002	15:29:50	263	235	91.9	69.2	65.7
15/04/2002	15:30:05	279.2	244	76.9	60.8	57.3
15/04/2002	15:30:20	272.4	248.3	75.4	58.6	53.5
15/04/2002	15:30:35	284.5	266.2	71.2	56.2	51.7
15/04/2002	15:30:51	257.6	236.2	68	53.1	49.6
15/04/2002	15:31:05	282.7	256.8	89.6	68.6	60.8
15/04/2002	15:31:20	305.4	277.2	98.4	73.6	65.5
15/04/2002	15:31:35	315	292.8	100.7	76.3	66.4
15/04/2002	15:31:51	308.1	280.4	103.5	75.6	68.5
15/04/2002	15:32:05	319.2	288.8	112.8	81.7	73.9
15/04/2002	15:32:20	345.8	332.2	94.8	75.1	67.4
15/04/2002	15:32:35	339.2	327.7	95.9	72.4	62.3
15/04/2002	15:32:50	346.3	331	88.8	63.4	53.4
15/04/2002	15:33:05	361.7	348.4	81.4	61.6	55.7
15/04/2002	15:33:20	364.6	355.2	75.8	57.3	53.7
15/04/2002	15:33:35	354.3	329.6	91.6	64.2	54.6
15/04/2002	15:33:51	373.3	325.2	115.5	77	59.9
15/04/2002	15:34:06	392	362	96.7	74.2	65.6
15/04/2002	15:34:20	382.6	343.5	124.4	84.8	69.9
15/04/2002	15:34:35	393.2	366.3	115.4	80.7	70.5
15/04/2002	15:34:50	400.8	375.2	97.7	69.2	61.2
15/04/2002	15:35:06	397.8	377.4	98.5	72.5	65.5
15/04/2002	15:35:20	405.7	377	107.3	72.3	63.3
15/04/2002	15:35:35	409.1	369.7	141.1	93.9	78.6
15/04/2002	15:35:50	424.3	390.7	143.7	91.3	81.6
15/04/2002	15:36:05	431.7	396.9	122.1	82.4	73.9
15/04/2002	15:36:20	424.3	406.1	110.5	79.6	70.3
15/04/2002	15:36:36	410	393.3	100.8	75.6	62.4
15/04/2002	15:36:51	415.3	389.5	89.6	70.9	60.2
15/04/2002	15:37:05	428	402	95.9	69.8	60.1
15/04/2002	15:37:21	441.7	398.5	105.3	76.2	67.9
15/04/2002	15:37:35	444.8	404.9	126.3	83.4	78
15/04/2002	15:37:50	443.4	417	134.9	90.2	80.2
15/04/2002	15:38:06	431.8	405.4	140.5	91.2	81
15/04/2002	15:38:20	439.1	401.1	149.8	94.7	85.3
15/04/2002	15:38:36	446.4	406.3	181.6	100.2	90.6
15/04/2002	15:38:51	447.9	432.1	155.3	95.8	87.3
15/04/2002	15:39:05	432	417.7	131.5	92.1	85.4
15/04/2002	15:39:20	430.1	430.1	139.1	84.7	78.9
15/04/2002	15:39:35	432.4	420.5	189.8	95.4	89

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15/04/2002	15:39:50	443.5	419.9	201.1	114.9	104.7
15/04/2002	15:40:05	452.1	434.8	161.7	103.1	92
15/04/2002	15:40:21	445.9	423.2	155.7	104.7	90.8
15/04/2002	15:40:35	450.1	416.6	181.2	104.8	90.6
15/04/2002	15:40:50	451.9	440.4	154.7	103.7	91.1
15/04/2002	15:41:05	456.2	451.4	139.7	93	85.2
15/04/2002	15:41:20	442.7	430.8	128.4	90.5	83.6
15/04/2002	15:41:36	446.9	452.4	115.6	84.7	77.6
15/04/2002	15:41:50	437	451.9	106.9	77.9	70.2
15/04/2002	15:42:05	426.7	427.4	105.5	67.2	60.9
15/04/2002	15:42:21	402.6	387.1	147.6	96.9	91
15/04/2002	15:42:36	394.6	368.8	216.7	131.1	120.3
15/04/2002	15:42:50	422.9	401.9	190.1	115.7	104.8
15/04/2002	15:43:05	417.6	408.3	158.2	105.9	96.1
15/04/2002	15:43:20	396.6	406.4	136.9	92.9	82.9
15/04/2002	15:43:35	380.5	376.5	170.4	102.1	85.3
15/04/2002	15:43:50	384.4	395.9	138.3	90.8	80.4
15/04/2002	15:44:05	365.5	354.4	162.5	103	93.5
15/04/2002	15:44:21	365.8	364.6	161.9	105	93.2
15/04/2002	15:44:36	373.9	373	132.8	90.3	75
15/04/2002	15:44:51	359.2	343.8	114	75.5	65.8
15/04/2002	15:45:05	344.4	335.4	107.8	75.6	69.6
15/04/2002	15:45:20	334.7	338.8	128.7	85.4	76.1
15/04/2002	15:45:36	314.4	321.4	113.7	84	71.9
15/04/2002	15:45:51	291.3	299.7	105.5	80.2	67
15/04/2002	15:46:05	278.5	273.1	98.7	83.3	73.3
15/04/2002	15:46:20	250.5	245.3	96	71.4	61.3
15/04/2002	15:46:35	221.9	215.9	97.7	69.3	62.4
15/04/2002	15:46:51	197.4	184.4	110.6	70.2	61.6
15/04/2002	15:47:05	182.4	169.3	104.5	68	62.7
15/04/2002	15:47:20	174.6	155.9	107.6	70.5	64.8
15/04/2002	15:47:35	178.1	169.2	103.8	67.6	59.3
15/04/2002	15:47:50	165.1	148.4	104.3	60	53
15/04/2002	15:48:05	146.9	129.9	94.4	64.5	57.4
15/04/2002	15:48:20	138.2	125.8	90.3	69.4	61.3
15/04/2002	15:48:35	131.3	124.2	92.1	66.3	58.7
15/04/2002	15:48:51	125.1	118.9	94.2	59.7	49.6
15/04/2002	15:49:05	120.2	113	81.5	55.8	48.8
15/04/2002	15:49:20	110.5	102.2	76.9	54.6	49.6
15/04/2002	15:49:35	113.3	99.8	74.4	56.3	48.7
15/04/2002	15:49:50	110	98.5	71.9	58.5	49.8

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15/04/2002	15:50:05	91.1	82.4	64.9	52.2	47.3
15/04/2002	15:50:21	96.3	84.7	67.6	55.6	51.9
15/04/2002	15:50:35	98.1	86.2	66.6	55.7	52.3
15/04/2002	15:50:51	101.8	89	66.6	54.3	49.8

Table A.19 Temperature Results on Point 3

Date	Clock	D010	D011	D012	D013	D014
15/04/2002	15:10:05	29.1	29.4	29.6	29.8	30
15/04/2002	15:10:21	29.1	29.5	29.7	29.8	30
15/04/2002	15:10:36	29.2	29.5	29.7	29.9	30
15/04/2002	15:10:51	29.1	29.5	29.7	29.9	30
15/04/2002	15:11:05	29.1	29.5	29.7	29.8	30
15/04/2002	15:11:20	29.1	29.4	29.7	29.8	30
15/04/2002	15:11:36	29.1	29.5	29.7	29.9	30
15/04/2002	15:11:50	29.2	29.6	29.8	29.9	30.1
15/04/2002	15:12:06	29.3	29.6	29.8	29.9	30.1
15/04/2002	15:12:20	29.1	29.5	29.7	29.8	30
15/04/2002	15:12:36	29.1	29.5	29.7	29.8	30
15/04/2002	15:12:51	35.1	30.3	30.2	30.6	30.8
15/04/2002	15:13:05	45	33.7	31.9	32	31.9
15/04/2002	15:13:20	54	38	33.7	33.4	33
15/04/2002	15:13:35	52.5	41	36.9	35.9	35.1
15/04/2002	15:13:51	44.5	38.5	36.4	35.6	35.2
15/04/2002	15:14:05	39.3	36.4	35.1	34.6	34.5
15/04/2002	15:14:20	41.4	35	33.4	33.3	33.1
15/04/2002	15:14:36	37.5	33.8	33	32.9	32.9
15/04/2002	15:14:50	34.1	32.5	33	33.6	33.5
15/04/2002	15:15:06	39.1	34.4	33.7	33.6	33.6
15/04/2002	15:15:20	42.1	35.1	34.1	33.7	33.3
15/04/2002	15:15:35	41.2	34.3	33.2	33.1	33.1
15/04/2002	15:15:50	42.9	34.5	33.4	32.5	32.5
15/04/2002	15:16:06	40.8	33	31.9	31.5	31.6
15/04/2002	15:16:21	42.1	36.9	33.7	32.7	32.5
15/04/2002	15:16:35	43.7	36.7	34.2	32.9	32.8
15/04/2002	15:16:51	43.6	36.6	35.2	34.1	33.9
15/04/2002	15:17:06	44.3	35.8	35.4	35.5	35.3
15/04/2002	15:17:20	48.2	36.2	35.3	34.9	34.8
15/04/2002	15:17:35	42.9	35.4	35.2	35.6	35.6
15/04/2002	15:17:50	47.1	36.6	36	35.1	34.9
15/04/2002	15:18:05	46.3	37.1	35.2	33.9	33.8
15/04/2002	15:18:20	46.2	35.8	34.5	33.9	33.9
15/04/2002	15:18:36	45.7	36.6	35.2	34.4	34.3
15/04/2002	15:18:50	46.9	38.5	36.6	35.6	35.1
15/04/2002	15:19:05	46.7	38.6	37.1	35.9	35.6

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15/04/2002	15:19:21	46.3	38.4	36.9	36.3	36
15/04/2002	15:19:35	48.8	38.2	37.3	36.3	36
15/04/2002	15:19:50	55.7	40.1	37.3	34.6	34.3
15/04/2002	15:20:05	54.5	39.6	36.7	35	34.8
15/04/2002	15:20:20	50	39.9	37.5	36.3	36.2
15/04/2002	15:20:36	54.2	42.4	39.8	38.2	37.6
15/04/2002	15:20:51	52.6	44.3	41.6	40.8	40.1
15/04/2002	15:21:06	57.9	46.1	42.1	41.3	40.8
15/04/2002	15:21:20	67.4	45.6	40.6	39.9	39.5
15/04/2002	15:21:36	71.4	45.8	41.2	40	39.7
15/04/2002	15:21:51	72.8	49.1	44.6	42.6	41.8
15/04/2002	15:22:05	72.3	52.7	46.1	42.7	42.1
15/04/2002	15:22:20	76.6	55.8	47.9	42.8	42.1
15/04/2002	15:22:35	83.6	57.4	48.2	43.1	42
15/04/2002	15:22:51	84.3	56.8	48.2	43.5	42.4
15/04/2002	15:23:06	92.1	59.8	51	45.7	45.3
15/04/2002	15:23:21	95.5	61.6	53.3	46.8	45.2
15/04/2002	15:23:35	107.3	66.9	54.6	47.6	44.3
15/04/2002	15:23:51	122.5	73	54.6	47	42
15/04/2002	15:24:06	125.5	80.8	59.7	49.9	46.2
15/04/2002	15:24:20	133.8	83.5	62.3	52	48.2
15/04/2002	15:24:36	142.2	83.8	59.9	49.6	46.5
15/04/2002	15:24:51	155.5	85.2	50.5	43.9	42.8
15/04/2002	15:25:06	157.5	92.8	55.3	42.1	40.8
15/04/2002	15:25:20	155.8	88.9	60.8	48.5	46.8
15/04/2002	15:25:35	150.4	93	67.8	55.1	52.5
15/04/2002	15:25:51	159.5	99	74.8	61.9	58.1
15/04/2002	15:26:05	158.1	98.6	75.7	68.2	64.3
15/04/2002	15:26:21	171.5	97.1	73.6	63.2	59.1
15/04/2002	15:26:35	187.4	98.6	58.9	53.5	51.1
15/04/2002	15:26:50	201	111.9	57.3	50.2	49.1
15/04/2002	15:27:05	205	114.1	68.1	56.7	52.5
15/04/2002	15:27:21	203.7	103.6	62.1	56.7	52.7
15/04/2002	15:27:35	204.3	101.9	71.8	61.2	58.4
15/04/2002	15:27:50	196.6	121.4	84.1	70.2	67.8
15/04/2002	15:28:06	202	126.9	84.9	68.8	65.7
15/04/2002	15:28:20	212.5	137.5	79.3	64.8	61.5
15/04/2002	15:28:35	222.7	144.2	80.6	65.2	60.8
15/04/2002	15:28:50	236.4	143.9	75	58	52.9
15/04/2002	15:29:05	248.1	160.5	83.2	62.5	57.5
15/04/2002	15:29:21	252	167.4	95.2	73	66.2

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15/04/2002	15:29:35	265.2	169.8	104.8	78.1	70.1
15/04/2002	15:29:50	270.1	170.9	101.2	77.4	69.8
15/04/2002	15:30:05	283.1	175.2	89.8	70.4	63.7
15/04/2002	15:30:20	294.2	188.8	90.4	61.8	57.6
15/04/2002	15:30:35	301.6	170.9	79.5	58.3	54.6
15/04/2002	15:30:51	303.8	177.1	63.2	51.8	49.6
15/04/2002	15:31:05	318.2	194.7	95.7	58.8	54.5
15/04/2002	15:31:20	327.1	204.6	105.7	70	61.8
15/04/2002	15:31:35	326.3	201.5	98.7	68.6	65.1
15/04/2002	15:31:51	339.6	210.6	114.8	78	69.6
15/04/2002	15:32:05	350.9	226.9	116.5	82.3	71.2
15/04/2002	15:32:20	343	218.8	109.4	77.3	68.8
15/04/2002	15:32:35	353.4	222.1	96.7	67.5	61.2
15/04/2002	15:32:50	351.2	225.9	89.4	61.5	57.5
15/04/2002	15:33:05	349.7	228.6	87.8	62.5	59.5
15/04/2002	15:33:20	343.1	228.1	85.1	62	59
15/04/2002	15:33:35	347.3	241.7	95.4	60.7	53.7
15/04/2002	15:33:51	366.2	244.4	112.5	75.2	68.2
15/04/2002	15:34:06	398.4	250.2	109.2	74.3	70.3
15/04/2002	15:34:20	382	262.5	118.1	81.6	75.4
15/04/2002	15:34:35	393.1	248.9	110.9	71.7	64.7
15/04/2002	15:34:50	387.8	265.8	101	64.6	63.2
15/04/2002	15:35:06	398	283.2	114.4	70.8	68.2
15/04/2002	15:35:20	369.4	266.6	108.8	70	68.9
15/04/2002	15:35:35	400.4	277.5	122.1	76.7	69.5
15/04/2002	15:35:50	390	286.3	131	89.8	82.4
15/04/2002	15:36:05	414.7	279.2	122.1	85.1	77.4
15/04/2002	15:36:20	427.2	262.5	115.9	81.2	71.5
15/04/2002	15:36:36	425	250.9	94.3	74	67.3
15/04/2002	15:36:51	408	266.2	89.1	63.6	62.2
15/04/2002	15:37:05	412	284.1	103.3	61.9	59.3
15/04/2002	15:37:21	424.3	294.5	124.6	76.1	68.6
15/04/2002	15:37:35	405.1	285.3	145.9	94.9	84.9
15/04/2002	15:37:50	401.9	284.9	150.4	105	94.2
15/04/2002	15:38:06	417.1	288.7	159.4	104.4	90.1
15/04/2002	15:38:20	445.2	297	151.9	99.6	78.5
15/04/2002	15:38:36	435.2	306.9	182.1	117.6	100.6
15/04/2002	15:38:51	431	303.5	167.6	108.6	96.1
15/04/2002	15:39:05	449.1	298.1	144.4	94.2	84.3
15/04/2002	15:39:20	396.4	293.5	148.6	90.4	75.7
15/04/2002	15:39:35	418	295.7	176.8	95	84.2

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15/04/2002	15:39:50	443.5	296.5	197.5	124	104.7
15/04/2002	15:40:05	408.8	305.1	164.5	114.5	103.1
15/04/2002	15:40:21	416.3	303.1	185.8	120	105.3
15/04/2002	15:40:35	413.7	305.8	191.3	124	112.6
15/04/2002	15:40:50	445.7	292.8	160.8	107	98.6
15/04/2002	15:41:05	436.3	304.2	134.2	86.4	80.9
15/04/2002	15:41:20	464.9	310.8	143.7	89	83.1
15/04/2002	15:41:36	404.8	296.4	142.6	91.6	84.8
15/04/2002	15:41:50	374.3	285	132.6	87	83.2
15/04/2002	15:42:05	409.6	265.4	104	82.1	77.5
15/04/2002	15:42:21	402.6	284.6	138.6	79.3	76.6
15/04/2002	15:42:36	424.1	298.7	196.5	134.5	122.3
15/04/2002	15:42:50	419.1	301.8	180.2	135	124.6
15/04/2002	15:43:05	400.6	295.2	161.8	117.1	109.7
15/04/2002	15:43:20	349.6	274.5	170.8	111.7	100.9
15/04/2002	15:43:35	345.9	270.8	178.8	123.1	112.2
15/04/2002	15:43:50	328.6	264.8	181.7	118.8	108.2
15/04/2002	15:44:05	323.7	255.7	186.1	125.8	109.6
15/04/2002	15:44:21	344	258.8	175.9	122.1	107.7
15/04/2002	15:44:36	340.2	248.4	140.2	98	91.6
15/04/2002	15:44:51	333.8	244.7	120.4	76.8	73
15/04/2002	15:45:05	351.6	268.3	138.4	72.7	66.9
15/04/2002	15:45:20	330.7	261.5	160.7	89.2	83.1
15/04/2002	15:45:36	316.5	230.4	126.9	80.7	77.5
15/04/2002	15:45:51	304.4	226	108.8	76.2	74.8
15/04/2002	15:46:05	276.7	200	109.5	72.1	73.5
15/04/2002	15:46:20	254	198.9	107	73	70.2
15/04/2002	15:46:35	216.9	185.2	119.2	85.1	80.4
15/04/2002	15:46:51	200.7	171.2	118.7	89.2	84.3
15/04/2002	15:47:05	183.9	159.2	120.7	91.8	83.9
15/04/2002	15:47:20	186.4	150.5	114	91.8	87.1
15/04/2002	15:47:35	182.8	144.6	100.4	80.3	76.4
15/04/2002	15:47:50	169.5	133.7	102.4	69	66.6
15/04/2002	15:48:05	155.1	121.1	103.6	74.5	70.5
15/04/2002	15:48:20	145.4	125.2	110.5	86.9	75
15/04/2002	15:48:35	140.7	124.2	108	90	82.4
15/04/2002	15:48:51	127	116.4	101.8	78.8	71.6
15/04/2002	15:49:05	117.6	107.2	91.8	65.8	60.6
15/04/2002	15:49:20	116.9	97.7	74.5	53.9	52.6
15/04/2002	15:49:35	108	93.8	81.1	65.7	61.7
15/04/2002	15:49:50	101.5	94.6	84.3	65.6	60.9

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15/04/2002	15:50:05	96.4	81.5	70.6	61.6	59.7
15/04/2002	15:50:21	94.1	81.9	71.6	47.3	44.2
15/04/2002	15:50:35	94.8	83.5	70.7	43.5	42.4
15/04/2002	15:50:51	97.3	85.9	72.8	43.7	40.2

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Table A.19 Temperature Results on Point 4

Date	Clock	D015	D016	D017	D018	D019
15/04/2002	15:10:05	30.2	30	30	30	30
15/04/2002	15:10:21	30.1	30.1	30	29.9	29.9
15/04/2002	15:10:36	30.2	30.1	30	30	29.9
15/04/2002	15:10:51	30.2	30.1	30.2	29.9	29.7
15/04/2002	15:11:05	30.1	30.1	30.2	30	29.8
15/04/2002	15:11:20	30.2	30.1	30.2	30.1	30
15/04/2002	15:11:36	30.2	30.1	30.3	30.3	30.3
15/04/2002	15:11:50	30.2	30.2	30.2	30.3	30.3
15/04/2002	15:12:06	30.3	30.2	30.2	29.9	29.8
15/04/2002	15:12:20	30.2	30.1	30.1	29.8	29.8
15/04/2002	15:12:36	30.2	30.1	30.1	29.8	29.7
15/04/2002	15:12:51	34.9	32.5	31.8	30.9	30
15/04/2002	15:13:05	43.8	37.1	33.4	32.7	31.7
15/04/2002	15:13:20	52.5	45.6	34.5	31.7	31.1
15/04/2002	15:13:35	53.2	45.3	32.2	31.2	32.4
15/04/2002	15:13:51	46.8	38.8	31.4	31	33.6
15/04/2002	15:14:05	39.2	34.8	31.6	31.8	33.4
15/04/2002	15:14:20	39.3	33.9	31.9	31.5	32.5
15/04/2002	15:14:36	36.2	33	32.2	32.1	32.7
15/04/2002	15:14:50	33.4	31.6	31.3	32.6	32.9
15/04/2002	15:15:06	38.4	34.4	33.1	32.4	32.5
15/04/2002	15:15:20	41.5	35.6	33.8	32.2	31.9
15/04/2002	15:15:35	39.8	35.8	33.9	33	32.6
15/04/2002	15:15:50	37.2	35	33	32.4	32.2
15/04/2002	15:16:06	34.8	32.4	31.2	31.6	31.8
15/04/2002	15:16:21	39.8	35.4	33.1	31.8	31.8
15/04/2002	15:16:35	43.4	36	33.1	32.2	32.3
15/04/2002	15:16:51	44.4	37	33	31.5	32.1
15/04/2002	15:17:06	44	38.1	32.8	31.2	32.3
15/04/2002	15:17:20	46.3	38	32.3	31	32.2
15/04/2002	15:17:35	43.6	37	34.4	31.7	31.7
15/04/2002	15:17:50	45.8	37.7	33.2	32.4	33
15/04/2002	15:18:05	44	36.9	32.4	31	32
15/04/2002	15:18:20	46	36.8	33.3	31.9	32.5
15/04/2002	15:18:36	45.7	40.4	36.8	33.5	31.9
15/04/2002	15:18:50	47.2	42.5	37	31.9	31.2
15/04/2002	15:19:05	47.3	43.9	37.8	32.5	31.4

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15/04/2002	15:19:21	47.1	44	36.2	31.8	31.6
15/04/2002	15:19:35	49.7	42.9	36.1	32.7	32.7
15/04/2002	15:19:50	52.7	38.4	33.5	31.7	32.2
15/04/2002	15:20:05	53.4	38.2	33.4	32.2	33
15/04/2002	15:20:20	48.7	37.9	32.7	32.2	33.6
15/04/2002	15:20:36	54.6	42.7	35.9	31.1	32.2
15/04/2002	15:20:51	56.3	44.9	34	30.3	33.4
15/04/2002	15:21:06	60.7	45.1	36.1	30.7	33.6
15/04/2002	15:21:20	65.1	48.1	38.2	32.1	33.3
15/04/2002	15:21:36	70	50.4	39	32.5	32
15/04/2002	15:21:51	72.7	56.7	41.4	30.5	30.9
15/04/2002	15:22:05	74.6	63.7	44.2	32.4	30.7
15/04/2002	15:22:20	78.7	69.4	46.6	34	31.2
15/04/2002	15:22:35	84.8	71.4	45.1	33.4	31.7
15/04/2002	15:22:51	89.7	68.3	44	33.9	33.2
15/04/2002	15:23:06	95.5	63.9	36.7	35.1	37.4
15/04/2002	15:23:21	98.8	64.7	37	31.1	35.5
15/04/2002	15:23:35	105.5	74.3	41.8	31	33.7
15/04/2002	15:23:51	114.9	81.8	46.5	33.8	32.3
15/04/2002	15:24:06	120	90.7	45	31.9	33.4
15/04/2002	15:24:20	126.5	94.8	43.9	33	34.9
15/04/2002	15:24:36	130.4	92.9	49	40.7	38.6
15/04/2002	15:24:51	140.4	87.4	38	37.9	38.6
15/04/2002	15:25:06	144.6	90.3	40	36.5	36.5
15/04/2002	15:25:20	139.1	84.3	43.1	40	41.9
15/04/2002	15:25:35	143.8	98.4	46.4	33.1	36.7
15/04/2002	15:25:51	156.1	109.7	52.1	31.3	35.4
15/04/2002	15:26:05	162.1	107	42.5	31.3	40.7
15/04/2002	15:26:21	163.2	104.6	41.9	35.5	42.6
15/04/2002	15:26:35	170.3	90.4	38.4	37.8	41.7
15/04/2002	15:26:50	182.2	102.5	50.8	38.1	37.6
15/04/2002	15:27:05	183.6	122.6	58.4	40.8	40.5
15/04/2002	15:27:21	185.4	99.7	46.2	42.3	45.3
15/04/2002	15:27:35	192.7	104.5	67.8	34.8	37.3
15/04/2002	15:27:50	191.2	141.1	86	52.9	35
15/04/2002	15:28:06	188.4	144.7	77.3	48.5	43.6
15/04/2002	15:28:20	198.6	174.5	86.4	42.4	36.8
15/04/2002	15:28:35	206.3	177.3	81.2	52.7	45
15/04/2002	15:28:50	214.3	183.9	56.3	39.8	41.7
15/04/2002	15:29:05	224.8	202.7	80.5	40.1	35.3
15/04/2002	15:29:21	232.1	205.6	102.9	42.3	35.5

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15/04/2002	15:29:35	237	206.6	82.9	35.7	40.8
15/04/2002	15:29:50	244.1	211.9	84.9	44.3	44.9
15/04/2002	15:30:05	251.9	215	72.6	38.9	42.8
15/04/2002	15:30:20	260.4	226.3	78	44.4	41.3
15/04/2002	15:30:35	260.1	212.7	67.6	46.7	43.9
15/04/2002	15:30:51	265	155.4	51.2	44.7	44.1
15/04/2002	15:31:05	279.1	213.9	84.1	42.3	43.8
15/04/2002	15:31:20	285.9	242	86.9	53.4	46.8
15/04/2002	15:31:35	286.8	254	63.8	46.4	50.7
15/04/2002	15:31:51	299.7	267.2	102.7	43.8	41.6
15/04/2002	15:32:05	309.6	284.2	83.7	37.7	45.3
15/04/2002	15:32:20	302.9	278.8	78.1	45.3	46
15/04/2002	15:32:35	308.9	264.3	81.5	41.3	43.9
15/04/2002	15:32:50	308.6	273.7	67.9	39.6	44.7
15/04/2002	15:33:05	309.7	279.6	73.2	47.2	45.2
15/04/2002	15:33:20	311.4	286.3	65.5	42.4	44.3
15/04/2002	15:33:35	316.3	298	67.1	37.2	44.6
15/04/2002	15:33:51	328.5	282.4	48.8	50.2	56.1
15/04/2002	15:34:06	347.5	303.5	73.2	54	51.4
15/04/2002	15:34:20	337.5	324.7	74.1	41.2	51.8
15/04/2002	15:34:35	346	312.7	57.3	45.5	56.2
15/04/2002	15:34:50	339.6	316	64.8	42.6	51.9
15/04/2002	15:35:06	346.5	326.2	102.4	47.9	47
15/04/2002	15:35:20	336.7	308.7	67.9	44.6	51.6
15/04/2002	15:35:35	349.8	342.5	73.4	40.9	53.2
15/04/2002	15:35:50	351.2	328.5	88.3	48.1	56.4
15/04/2002	15:36:05	365.2	331.7	98.8	71	55.1
15/04/2002	15:36:20	379	325.6	96	68.1	56.5
15/04/2002	15:36:36	364.8	304.1	80.2	59.9	52.4
15/04/2002	15:36:51	354.6	312.7	64.6	56	52.8
15/04/2002	15:37:05	358.4	322.6	81.3	42.4	48.6
15/04/2002	15:37:21	373.6	337.2	100.1	69.1	48.7
15/04/2002	15:37:35	358	332	126.3	89.5	51
15/04/2002	15:37:50	357.2	328.3	147.5	78.2	53.2
15/04/2002	15:38:06	365.2	339.8	184.3	55.5	48.7
15/04/2002	15:38:20	389.9	354.9	160.5	42.9	45.1
15/04/2002	15:38:36	381.7	355.3	189.2	50.3	41.1
15/04/2002	15:38:51	372.2	339.8	143.1	67.2	59.8
15/04/2002	15:39:05	385	336.9	120.5	66.5	58.6
15/04/2002	15:39:20	343.9	320.3	81.6	51	55
15/04/2002	15:39:35	329	172.9	56.2	66.7	67.7

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15/04/2002	15:39:50	375.1	260.1	70.9	62.8	74.4
15/04/2002	15:40:05	361.6	301.6	75.6	70.7	68.2
15/04/2002	15:40:21	358.7	322.5	159.1	62.7	41.1
15/04/2002	15:40:35	366.7	344.7	149.4	56.4	50.5
15/04/2002	15:40:50	386.5	311.8	103.9	63.7	60.8
15/04/2002	15:41:05	386.4	312.1	79.7	61.6	62.3
15/04/2002	15:41:20	408.1	352.4	146.9	62.1	55.2
15/04/2002	15:41:36	358	324.7	119.8	51.8	51.6
15/04/2002	15:41:50	323.9	294.9	114.8	56.9	50.9
15/04/2002	15:42:05	352.8	291.4	93.1	60	55.6
15/04/2002	15:42:21	352.6	299.7	77.2	47.4	51.4
15/04/2002	15:42:36	381.6	330.4	176.1	57	47.6
15/04/2002	15:42:50	371.3	335.4	174.3	121	83.3
15/04/2002	15:43:05	355.1	322.8	154.8	88.3	65.7
15/04/2002	15:43:20	308.5	295.2	192.3	69.1	47.5
15/04/2002	15:43:35	313.8	296.9	218.9	46.2	39.6
15/04/2002	15:43:50	292.8	282	201.1	61.2	54.7
15/04/2002	15:44:05	293.3	281.9	150.8	51	54.8
15/04/2002	15:44:21	306.7	277.8	157.1	45.1	52.8
15/04/2002	15:44:36	301.4	286.5	118.4	54.5	56.5
15/04/2002	15:44:51	298.4	277.1	84.9	52.7	55.9
15/04/2002	15:45:05	311.2	287.7	132.4	53.5	54.2
15/04/2002	15:45:20	287.7	267	157.1	71.6	52.3
15/04/2002	15:45:36	277.2	265	118.4	65.3	57.1
15/04/2002	15:45:51	272.2	262.2	95.6	61.9	56.2
15/04/2002	15:46:05	234.4	198.8	95.3	61.6	54.4
15/04/2002	15:46:20	227.1	210.8	110.3	72.6	51.3
15/04/2002	15:46:35	198.6	187.6	125.8	65.6	42.4
15/04/2002	15:46:51	186.5	175.4	125.6	54.4	38.6
15/04/2002	15:47:05	171.4	161.7	121.3	47.4	40.1
15/04/2002	15:47:20	172.3	162.2	121.6	61.1	42.4
15/04/2002	15:47:35	170.7	157.3	101.8	53.2	44.8
15/04/2002	15:47:50	158.9	148.4	73.3	44	44.8
15/04/2002	15:48:05	144.3	128.7	79.4	43.8	37.6
15/04/2002	15:48:20	137	129.6	91.4	42.4	40.6
15/04/2002	15:48:35	133.5	129.6	102.7	55.8	39.2
15/04/2002	15:48:51	122.1	116.8	97.9	61.2	46.5
15/04/2002	15:49:05	112.9	108.5	65.4	51.2	46.2
15/04/2002	15:49:20	110.4	84.8	45.3	41.1	44.8
15/04/2002	15:49:35	109.3	95.1	63.9	40.4	36.2
15/04/2002	15:49:50	103.1	79.6	47.6	39.6	44.1

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15/04/2002	15:50:05	92.6	70.7	47.9	34.4	38.9
15/04/2002	15:50:21	92.3	77.2	44.2	35.1	42.7
15/04/2002	15:50:35	93.6	82.9	53.3	38.7	39.5
15/04/2002	15:50:51	94.9	87.2	66	44.8	40.6

Table A.20 Temperature Results on Point 5

Date	Clock	D020	D021	D022	D023	D024
15/04/2002	15:10:05	29.2	29.4	29.6	29.7	29.8
15/04/2002	15:10:21	29.2	29.5	29.6	29.7	29.8
15/04/2002	15:10:36	29.2	29.5	29.6	29.7	29.7
15/04/2002	15:10:51	29.2	29.5	29.6	29.8	29.8
15/04/2002	15:11:05	29.1	29.4	29.6	29.8	29.9
15/04/2002	15:11:20	29.1	29.4	29.6	29.8	29.9
15/04/2002	15:11:36	29.1	29.4	29.6	29.8	29.9
15/04/2002	15:11:50	29.3	29.6	29.7	29.9	30
15/04/2002	15:12:06	29.2	29.6	29.8	29.9	29.9
15/04/2002	15:12:20	29.1	29.5	29.6	29.9	29.9
15/04/2002	15:12:36	29.1	29.4	29.7	29.9	29.9
15/04/2002	15:12:51	30.3	30.2	30.2	30.2	30.3
15/04/2002	15:13:05	40.8	36.4	33.1	31.2	30.7
15/04/2002	15:13:20	51.5	39.9	35.1	33.2	32.8
15/04/2002	15:13:35	48.2	41	36.5	33.8	32.8
15/04/2002	15:13:51	40.4	37	34	32.4	32.2
15/04/2002	15:14:05	35	34.1	32.7	32.3	32.2
15/04/2002	15:14:20	36.5	33.9	32.3	32.1	31.9
15/04/2002	15:14:36	35.3	33.8	32.4	32.3	32.1
15/04/2002	15:14:50	31.5	31.5	31.5	32	32.2
15/04/2002	15:15:06	35.9	34.2	32.9	32.8	32.5
15/04/2002	15:15:20	36.8	34.8	33.4	33	32.5
15/04/2002	15:15:35	36.4	33.5	32.5	32.6	32.3
15/04/2002	15:15:50	42.4	36.7	32.4	31.9	31.7
15/04/2002	15:16:06	40.1	35.2	32.2	32.1	32.1
15/04/2002	15:16:21	37.5	35	33.4	32.6	32.4
15/04/2002	15:16:35	36.5	33.8	33.1	32.8	32.7
15/04/2002	15:16:51	38.1	34.5	33	32.1	32.1
15/04/2002	15:17:06	36.8	34.5	33.5	31.8	31.5
15/04/2002	15:17:20	40	36.4	33.5	32.1	32.1
15/04/2002	15:17:35	37.2	34.8	33.2	33	32.7
15/04/2002	15:17:50	39.7	35.2	33	32.6	32.7
15/04/2002	15:18:05	39.5	36.2	33.9	33.4	33.2
15/04/2002	15:18:20	38.7	35.6	33.9	33.5	33.2
15/04/2002	15:18:36	38.1	34.9	33.7	33.8	33.8
15/04/2002	15:18:50	37	35.7	34.1	34.2	33.9
15/04/2002	15:19:05	35.2	34.6	34.2	34.4	34.3

APPENDIX A

15/04/2002	15:19:21	35.7	34.8	34.3	34.3	33.8
15/04/2002	15:19:35	39.5	36.1	34.9	34.5	34.2
15/04/2002	15:19:50	44	38.2	34.9	32.8	32.7
15/04/2002	15:20:05	39.8	35.4	35.2	34.2	33.9
15/04/2002	15:20:20	36.3	35.1	33.9	33.6	33.7
15/04/2002	15:20:36	35.3	34.7	34.5	34	34
15/04/2002	15:20:51	34.8	35.1	35.8	33.8	33.2
15/04/2002	15:21:06	36.1	35.1	35.2	34.4	34.2
15/04/2002	15:21:20	47.7	42.8	39.3	36.5	34.9
15/04/2002	15:21:36	53.2	46.4	40.9	36.9	35.5
15/04/2002	15:21:51	41.8	40.8	40.4	39	37.3
15/04/2002	15:22:05	40	39.4	39.8	39.3	37.8
15/04/2002	15:22:20	53.3	48.5	44.4	43.1	40.6
15/04/2002	15:22:35	62.6	54.5	49.3	43.9	41.1
15/04/2002	15:22:51	62.6	54.4	49	44.8	41.8
15/04/2002	15:23:06	57.2	48.7	41.9	37.7	37.5
15/04/2002	15:23:21	71.2	59.1	47.5	38	35.2
15/04/2002	15:23:35	89.6	70.8	52.9	44.1	39.5
15/04/2002	15:23:51	106.5	87.9	51.3	44.2	41.1
15/04/2002	15:24:06	108.9	89.5	56.5	44.4	41
15/04/2002	15:24:20	118.2	91.6	61.9	46.2	41.7
15/04/2002	15:24:36	131.1	99.3	57.2	45.9	42.2
15/04/2002	15:24:51	151.1	98.4	46	41	39.4
15/04/2002	15:25:06	145.3	98.3	52.8	46.8	44.7
15/04/2002	15:25:20	144.4	100.7	58.9	50.9	46.6
15/04/2002	15:25:35	137.4	107.4	72.5	55.9	44.9
15/04/2002	15:25:51	129.2	98.9	77	59.7	50.5
15/04/2002	15:26:05	100.6	80.7	68.6	47.9	40.1
15/04/2002	15:26:21	141.2	102.6	68.4	53.5	47.7
15/04/2002	15:26:35	175.8	116.8	56.6	47.1	44.7
15/04/2002	15:26:50	178.7	123.2	63.1	50.3	45.9
15/04/2002	15:27:05	186.1	138	73.1	59.7	52.7
15/04/2002	15:27:21	171	111.7	51.9	49	48
15/04/2002	15:27:35	138.1	95.9	73.8	64.5	58.3
15/04/2002	15:27:50	151	120.2	88.9	74.7	66.4
15/04/2002	15:28:06	181.6	141.4	82.1	65.4	61.7
15/04/2002	15:28:20	202.1	158.5	78.2	64.4	58.7
15/04/2002	15:28:35	213.9	171.1	75.4	59.6	55.3
15/04/2002	15:28:50	233.6	169.2	72.1	52.9	47.9
15/04/2002	15:29:05	236.1	167.2	90	68.7	61.3
15/04/2002	15:29:21	237.8	194	98.1	76.8	67.4

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15/04/2002	15:29:35	245.9	191.4	109.4	80.5	63.2
15/04/2002	15:29:50	265.5	204.2	102.2	73.4	61.3
15/04/2002	15:30:05	278.3	209.7	80.8	55.1	49.7
15/04/2002	15:30:20	282.3	216.1	89.6	57.3	50.1
15/04/2002	15:30:35	292.3	215.5	77.4	57.6	50.3
15/04/2002	15:30:51	275.1	220.3	70.3	54.3	48.2
15/04/2002	15:31:05	291.6	226.8	111.7	69.9	57.4
15/04/2002	15:31:20	304.1	234.5	122.7	81.1	66
15/04/2002	15:31:35	315.2	243.9	124.7	63.8	54.3
15/04/2002	15:31:51	317.5	247.1	115.7	78.2	66.6
15/04/2002	15:32:05	329.4	266.1	121.5	75.1	58.8
15/04/2002	15:32:20	349.4	269.3	101.3	61.7	54.8
15/04/2002	15:32:35	344.3	287.1	104.3	67.7	57.1
15/04/2002	15:32:50	342.9	267.4	107.3	47.8	47.6
15/04/2002	15:33:05	359.5	266.6	90.6	53.5	50.9
15/04/2002	15:33:20	367.5	280.9	79.2	54.1	50.2
15/04/2002	15:33:35	359.3	287.1	108.6	57.1	49.5
15/04/2002	15:33:51	363.3	294.1	135.3	69.3	56
15/04/2002	15:34:06	392.8	315.8	116.2	74.6	59.8
15/04/2002	15:34:20	385.5	317.5	152.3	66.5	54.3
15/04/2002	15:34:35	391.4	307.4	131.6	65.7	58.1
15/04/2002	15:34:50	393.5	306.4	109.5	62.1	56.7
15/04/2002	15:35:06	414.7	328.6	122.3	82.1	68.4
15/04/2002	15:35:20	399.8	327.6	126.8	67	54.3
15/04/2002	15:35:35	400.7	325.3	163	92.7	64.1
15/04/2002	15:35:50	418.3	351.3	155.1	91.6	65
15/04/2002	15:36:05	409	353.9	119.1	80.4	65.8
15/04/2002	15:36:20	392.9	347.2	113	80.3	64.6
15/04/2002	15:36:36	390.5	333.6	100.4	77.1	59.5
15/04/2002	15:36:51	375.7	344.2	92.7	71.6	59.8
15/04/2002	15:37:05	406.9	359.8	105.3	66.7	56.1
15/04/2002	15:37:21	432.1	373.2	129.9	81.7	70.1
15/04/2002	15:37:35	440.9	363.6	136.8	96.4	85.4
15/04/2002	15:37:50	443.6	363.7	131.8	98.2	84.1
15/04/2002	15:38:06	446.4	364.4	149.5	98.7	81.8
15/04/2002	15:38:20	443.3	363.8	154.3	104.6	76.8
15/04/2002	15:38:36	473.4	392.4	180.6	120.4	101.9
15/04/2002	15:38:51	479.1	399.6	154	104.1	90.5
15/04/2002	15:39:05	458.9	396.2	125.6	90.2	80
15/04/2002	15:39:20	480.7	394.8	174.9	93.2	78.4
15/04/2002	15:39:35	391.6	257.8	103.1	89.9	83.4

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15/04/2002	15:39:50	463.4	357.9	160.8	130.7	91.6
15/04/2002	15:40:05	476.9	396.2	155.3	89.6	75.2
15/04/2002	15:40:21	475.6	401.7	179.8	104.4	88
15/04/2002	15:40:35	462.1	391.5	199.6	111.8	83.1
15/04/2002	15:40:50	449.1	385.3	163.3	105.5	83.9
15/04/2002	15:41:05	448.7	391.3	163.1	95.4	77.4
15/04/2002	15:41:20	455.8	400.9	154.6	95.4	78
15/04/2002	15:41:36	457.2	403	145.1	85.8	71.8
15/04/2002	15:41:50	450.9	399.1	121.6	80.3	69.2
15/04/2002	15:42:05	417.4	379.4	108.6	82.6	68
15/04/2002	15:42:21	389.2	358	168.5	110.8	73.4
15/04/2002	15:42:36	397.7	354.3	203.6	153.9	122.4
15/04/2002	15:42:50	411.4	373.7	177.3	128.6	100.4
15/04/2002	15:43:05	418.4	371.9	146.8	105.6	84
15/04/2002	15:43:20	395.8	350.1	148.1	93.9	81.9
15/04/2002	15:43:35	382	334.8	173.2	107.5	92.4
15/04/2002	15:43:50	386.1	346.1	179.3	111.3	85.2
15/04/2002	15:44:05	359.9	326.3	186.3	121.4	99.3
15/04/2002	15:44:21	351.5	324.2	178.4	115.4	86.9
15/04/2002	15:44:36	366.7	323.2	135.9	92.8	75.3
15/04/2002	15:44:51	342.9	317.1	115.2	83.4	68.9
15/04/2002	15:45:05	340.1	314.4	123.4	93.4	76.5
15/04/2002	15:45:20	343.9	315.7	137.6	96.3	78
15/04/2002	15:45:36	336.2	302.4	112	83.9	72.8
15/04/2002	15:45:51	316.6	292.1	102.5	78.9	68.4
15/04/2002	15:46:05	287.1	266.2	105.7	76.1	69
15/04/2002	15:46:20	255.3	236.7	103.7	74.3	66.2
15/04/2002	15:46:35	221.5	208.9	118	87.6	78.3
15/04/2002	15:46:51	192.3	184.5	114.6	82.2	77.3
15/04/2002	15:47:05	180.1	171.9	115.8	86.2	78.8
15/04/2002	15:47:20	171.9	164.7	114.8	79.8	73.6
15/04/2002	15:47:35	177.8	169	96	66.2	62.7
15/04/2002	15:47:50	167.4	153.9	100.9	61.7	55.7
15/04/2002	15:48:05	148.3	132.4	101.8	74.8	64.6
15/04/2002	15:48:20	138.7	129.9	108.3	84.3	72.9
15/04/2002	15:48:35	134.9	128.4	107	76.8	67.5
15/04/2002	15:48:51	129.3	120.9	98.7	65.8	55.6
15/04/2002	15:49:05	122.9	114.8	89.6	60.2	52.2
15/04/2002	15:49:20	118	104.9	85.7	62	56.8
15/04/2002	15:49:35	110.7	99.3	87	64.5	57.8
15/04/2002	15:49:50	106.3	96.7	81.3	53.3	49

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15/04/2002	15:50:05	88.5	75.3	61.6	52.1	46.6
15/04/2002	15:50:21	92.4	82	71.5	52.1	44
15/04/2002	15:50:35	95.8	86.3	75.2	57.1	48.7
15/04/2002	15:50:51	100.1	90.8	74.9	56.5	50.8

APPENDIX A

Table A.21 Temperature Results on Point 6

Date	Clock	D025	D026	D027	D028	D029
15/04/2002	15:10:05	30.1	30.1	30.1	30.1	30.1
15/04/2002	15:10:21	30.1	30.1	30	29.9	30.1
15/04/2002	15:10:36	30.1	30.2	30	29.9	30.1
15/04/2002	15:10:51	30.2	30.2	30.1	30	30.1
15/04/2002	15:11:05	30.2	30.1	30	30.1	30.1
15/04/2002	15:11:20	30.1	30.1	30.1	30.1	30.1
15/04/2002	15:11:36	30.1	30.1	30.1	30.2	30.2
15/04/2002	15:11:50	30.2	30.3	30.2	30.3	30.4
15/04/2002	15:12:06	30.2	30.2	30.1	29.9	30
15/04/2002	15:12:20	30.1	30.2	30	29.9	30
15/04/2002	15:12:36	30.1	30.1	30	29.9	30
15/04/2002	15:12:51	31.8	32.9	31.8	30.9	30.9
15/04/2002	15:13:05	39	39.6	33.5	32.1	31.9
15/04/2002	15:13:20	46.3	47	36.5	31.6	31.5
15/04/2002	15:13:35	48.8	47.9	39.5	32.2	31.9
15/04/2002	15:13:51	44.2	41.4	35.7	33.5	33.6
15/04/2002	15:14:05	38.4	36	33.5	33	33.1
15/04/2002	15:14:20	39	36.2	33.7	32.9	32.9
15/04/2002	15:14:36	37.8	35.8	33.4	32.7	32.6
15/04/2002	15:14:50	34.7	33.7	32.8	32.5	32.5
15/04/2002	15:15:06	37.6	35.1	33.1	33.3	33.4
15/04/2002	15:15:20	39.9	37.2	34.7	32.9	32.6
15/04/2002	15:15:35	39.3	37	34.7	33.3	32.9
15/04/2002	15:15:50	42.2	37.7	33.4	32.5	32.4
15/04/2002	15:16:06	40.8	36.6	33.5	32.3	32.2
15/04/2002	15:16:21	40.5	37.8	35	33.5	32.8
15/04/2002	15:16:35	40.4	37.4	36	33.9	33.1
15/04/2002	15:16:51	41.7	38.5	36.2	32.9	32.4
15/04/2002	15:17:06	42.5	38.5	34.9	34.2	34
15/04/2002	15:17:20	44.8	39.6	35.7	34.8	34
15/04/2002	15:17:35	42.4	37.5	34.9	33.8	33.2
15/04/2002	15:17:50	42	38.6	36.4	34.6	33.6
15/04/2002	15:18:05	42.8	41	38.1	34.1	33.1
15/04/2002	15:18:20	42.4	39.6	36.7	34.6	34.3
15/04/2002	15:18:36	43.4	41.5	37.6	33.1	32.3
15/04/2002	15:18:50	45	42.8	37.8	33.2	32.1
15/04/2002	15:19:05	44.9	43	38.2	34.4	32.7

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15/04/2002	15:19:21	44.7	42.7	38.1	35.5	33.9
15/04/2002	15:19:35	46.6	42.1	38	36	35.6
15/04/2002	15:19:50	49.3	44.7	37.7	35.5	34.3
15/04/2002	15:20:05	49.2	42.1	36.8	36.4	35.5
15/04/2002	15:20:20	44.2	39.4	35.9	35.9	35.4
15/04/2002	15:20:36	50.8	44	37.1	37.4	37
15/04/2002	15:20:51	50.7	43	34.9	37.2	38.1
15/04/2002	15:21:06	53	47.9	38.7	39.4	41.5
15/04/2002	15:21:20	58.4	50.2	43.2	37.7	38.4
15/04/2002	15:21:36	63.8	55.4	45.1	38.5	37.4
15/04/2002	15:21:51	65.1	58.8	47.6	41.1	38.3
15/04/2002	15:22:05	65.2	62	48	43.3	40
15/04/2002	15:22:20	69.9	67.1	51.3	36.9	35.5
15/04/2002	15:22:35	79.5	69.9	48.9	35.5	34.5
15/04/2002	15:22:51	81.9	74.6	52.1	35.6	34.9
15/04/2002	15:23:06	84.7	72.2	58.7	40.6	36.3
15/04/2002	15:23:21	89.8	74.5	61.2	40.4	38.5
15/04/2002	15:23:35	93.4	84	60.9	38.3	37.1
15/04/2002	15:23:51	102	94.3	60.6	39.1	36
15/04/2002	15:24:06	108.3	101.3	66.1	37.7	35.7
15/04/2002	15:24:20	113.4	106.4	66.9	38.4	36.6
15/04/2002	15:24:36	116.8	109.9	60.8	41.7	39.2
15/04/2002	15:24:51	129.3	95.5	53.7	40.2	38.3
15/04/2002	15:25:06	130.3	103.5	58.7	38.5	37.7
15/04/2002	15:25:20	128.1	100.3	65.8	44.5	41
15/04/2002	15:25:35	126.7	110.6	76.4	43.7	40.7
15/04/2002	15:25:51	135.6	127.9	91.5	43.3	39.9
15/04/2002	15:26:05	137.2	124.5	93.9	56.7	43.4
15/04/2002	15:26:21	147.2	133.7	77.5	53.1	44.1
15/04/2002	15:26:35	154.9	132.2	54.7	47	42.3
15/04/2002	15:26:50	162.7	136.7	68.6	42.4	40.3
15/04/2002	15:27:05	167.2	139.5	71	42.4	40.7
15/04/2002	15:27:21	156.1	124.4	71.1	44.6	42.9
15/04/2002	15:27:35	164.2	138.6	95.5	45.2	43.1
15/04/2002	15:27:50	176.4	154.2	101	47.1	40.3
15/04/2002	15:28:06	173.7	157.9	80.2	48.2	45.4
15/04/2002	15:28:20	185.9	171.2	94.9	47.6	43
15/04/2002	15:28:35	184.2	176.1	89.7	56.2	48
15/04/2002	15:28:50	192.2	187.5	77.8	52.6	47.2
15/04/2002	15:29:05	201.1	199.5	106.1	48.6	43
15/04/2002	15:29:21	202.3	204.4	113.9	56.9	44.9

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15/04/2002	15:29:35	211.6	201.5	118.7	61	47.7
15/04/2002	15:29:50	216.6	209.5	103.8	58.1	47.5
15/04/2002	15:30:05	238.6	222	89	53.6	47.8
15/04/2002	15:30:20	239.5	229.3	96.2	52.1	47.5
15/04/2002	15:30:35	247.7	229.5	76.6	49.6	46.8
15/04/2002	15:30:51	243.8	230.3	75.2	48.5	45.4
15/04/2002	15:31:05	251.3	240.3	101	55.8	45.7
15/04/2002	15:31:20	260	254.2	123	55.9	45.8
15/04/2002	15:31:35	258.9	245.7	120.6	57.5	53
15/04/2002	15:31:51	263.2	261.2	137.4	74	54.6
15/04/2002	15:32:05	273.9	274.7	114	79.7	55.1
15/04/2002	15:32:20	272.9	267.5	112	64.8	53.5
15/04/2002	15:32:35	283.9	280.1	113	64.1	55
15/04/2002	15:32:50	277.6	273.5	114.1	57.3	51.4
15/04/2002	15:33:05	291.6	275.3	84.4	54.1	50.9
15/04/2002	15:33:20	297.9	288.7	74.9	52.1	50.1
15/04/2002	15:33:35	292.1	291.8	112.9	57.3	50.6
15/04/2002	15:33:51	293.7	273.4	143.4	73.8	61.8
15/04/2002	15:34:06	306.6	300.6	137.2	65.1	61
15/04/2002	15:34:20	300.8	298.8	132.5	76	61.2
15/04/2002	15:34:35	316.2	315	90	72.4	61.5
15/04/2002	15:34:50	314.1	310.4	105	62.6	57.3
15/04/2002	15:35:06	327.7	322.2	143	60.1	55
15/04/2002	15:35:20	312.5	315.2	152.4	60.8	57.1
15/04/2002	15:35:35	320.6	325.2	150.8	90.6	62.6
15/04/2002	15:35:50	326.1	337.1	147.6	85.4	64.4
15/04/2002	15:36:05	330	334.9	131.3	76	63.4
15/04/2002	15:36:20	328.9	330.6	117.7	71.3	59.9
15/04/2002	15:36:36	326.2	327	91.9	62.5	54.2
15/04/2002	15:36:51	315.4	324	89.6	60.3	53.8
15/04/2002	15:37:05	326.8	334.9	125.9	60.6	54.5
15/04/2002	15:37:21	326.6	339.8	172.1	64.3	58.9
15/04/2002	15:37:35	329.8	341.3	210.7	70.8	60.3
15/04/2002	15:37:50	330.4	341.2	217.5	71.1	61.5
15/04/2002	15:38:06	342.4	349.6	251.8	76.3	64.2
15/04/2002	15:38:20	350.3	358.3	257.9	84.7	64.9
15/04/2002	15:38:36	358.6	371.1	289.9	92.1	66.1
15/04/2002	15:38:51	359.5	370	208.4	86	68.3
15/04/2002	15:39:05	360.3	372.5	159.4	75.3	62.4
15/04/2002	15:39:20	362	338.2	189.3	71.4	60.7
15/04/2002	15:39:35	281.3	190.6	175.7	93.8	78.5

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15/04/2002	15:39:50	335	322.6	197.5	121.5	94.5
15/04/2002	15:40:05	359.5	362.7	185.2	94.3	82.2
15/04/2002	15:40:21	360.4	373.3	267.5	88.5	72.7
15/04/2002	15:40:35	357.1	373	293.4	96.4	72
15/04/2002	15:40:50	358.5	366.4	216.2	85.1	69.6
15/04/2002	15:41:05	344	351.6	194.4	82.1	67.3
15/04/2002	15:41:20	361.7	372.3	204.8	77.8	66.4
15/04/2002	15:41:36	351	366.5	173.8	72.1	64.3
15/04/2002	15:41:50	347.5	362.2	141.7	64.6	59.7
15/04/2002	15:42:05	349.8	357.9	114.1	64	57.5
15/04/2002	15:42:21	321	328.8	168.9	98.8	60.4
15/04/2002	15:42:36	324.4	343.9	243.2	147.7	81.4
15/04/2002	15:42:50	323.7	346.8	237.8	113.7	82
15/04/2002	15:43:05	326.3	343.7	193.6	93	74.8
15/04/2002	15:43:20	312	323.5	219.5	78.4	67.2
15/04/2002	15:43:35	296.9	310	250.3	94	68.6
15/04/2002	15:43:50	299.5	311	208.1	85.9	66.7
15/04/2002	15:44:05	279.6	290.7	179.1	100.9	78.4
15/04/2002	15:44:21	283.1	293.7	189.3	93.2	73.3
15/04/2002	15:44:36	302.3	307.9	135.5	74.9	63.2
15/04/2002	15:44:51	286.4	299.3	117.5	68.3	59.3
15/04/2002	15:45:05	289.1	302.6	157.4	73.2	61.2
15/04/2002	15:45:20	281.7	296.9	193.9	81.1	65.2
15/04/2002	15:45:36	285.7	297.2	149.7	70.4	60.8
15/04/2002	15:45:51	276.2	282.8	116.5	67	58.7
15/04/2002	15:46:05	236.6	209.3	119.5	76.2	66.4
15/04/2002	15:46:20	226.6	220.8	129	65.2	59
15/04/2002	15:46:35	200.4	199.6	148.3	72.5	68
15/04/2002	15:46:51	183.8	185.6	152.9	70.6	64.9
15/04/2002	15:47:05	171.6	175.1	135.6	80.6	67.9
15/04/2002	15:47:20	160.9	167.1	145.7	75.5	61.6
15/04/2002	15:47:35	164.3	168.3	112.5	60.6	55.5
15/04/2002	15:47:50	156.6	158.8	114.2	62.2	54.1
15/04/2002	15:48:05	144.4	143.2	102.8	71.7	65.8
15/04/2002	15:48:20	138.3	137.2	102.9	83.7	71.5
15/04/2002	15:48:35	135.2	135.4	118.6	77.8	64.4
15/04/2002	15:48:51	129.3	127.9	113.5	70.2	58.6
15/04/2002	15:49:05	122.4	120.6	91.8	66.8	55.7
15/04/2002	15:49:20	116.9	110.6	85.2	72.6	63.7
15/04/2002	15:49:35	111.1	106.2	91.1	60.4	55.1
15/04/2002	15:49:50	105.8	92.2	86.3	60.3	50.3

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15/04/2002	15:50:05	90.2	82.8	70.7	55.5	51.6
15/04/2002	15:50:21	92.1	80	60	52.3	48.4
15/04/2002	15:50:35	96.5	90.4	72.8	57.5	51.2
15/04/2002	15:50:51	98.1	93.9	83	59.3	48.8

Table A.22 Temperature Results on Point 7 and Point 8

Date	Clock	D030	D031	D032	D033	D034	D035
15/04/2002	15:10:05	29.4	29.3	29.3	29.5	29.5	29.5
15/04/2002	15:10:21	29.4	29.3	29.3	29.4	29.5	29.5
15/04/2002	15:10:36	29.4	29.4	29.3	29.5	29.6	29.6
15/04/2002	15:10:51	29.3	29.3	29.2	29.4	29.5	29.5
15/04/2002	15:11:05	29.3	29.3	29.2	29.4	29.5	29.5
15/04/2002	15:11:20	29.3	29.3	29.3	29.4	29.5	29.5
15/04/2002	15:11:36	29.3	29.3	29.3	29.4	29.5	29.5
15/04/2002	15:11:50	29.4	29.4	29.4	29.4	29.5	29.5
15/04/2002	15:12:06	29.4	29.4	29.4	29.5	29.5	29.6
15/04/2002	15:12:20	29.3	29.3	29.3	29.5	29.6	29.6
15/04/2002	15:12:36	29.3	29.3	29.3	29.5	29.5	29.5
15/04/2002	15:12:51	29.4	29.4	29.5	29.5	29.5	29.5
15/04/2002	15:13:05	31.4	31	30	29.5	29.6	29.5
15/04/2002	15:13:20	36	32.7	30.8	29.7	30.2	29.8
15/04/2002	15:13:35	38.2	34.8	32.1	30.8	30.8	30
15/04/2002	15:13:51	36	34	32.7	31	30.9	30.3
15/04/2002	15:14:05	34.5	33.1	32.4	31	30.8	30.6
15/04/2002	15:14:20	33	32.2	31.6	30.9	31	30.9
15/04/2002	15:14:36	33.6	32.2	31.5	30.9	31	30.7
15/04/2002	15:14:50	32.9	32.2	31.4	30.9	31	30.6
15/04/2002	15:15:06	32	31.5	31.2	30.7	30.8	30.5
15/04/2002	15:15:20	31.6	31.3	31.1	30.7	30.7	30.4
15/04/2002	15:15:35	31.2	31	31	30.5	30.6	30.5
15/04/2002	15:15:50	31.9	30.8	30.8	30.3	30.4	30.4
15/04/2002	15:16:06	34.8	32.2	31.8	30.3	30.7	30.4
15/04/2002	15:16:21	33.2	31.5	31.3	30.5	30.7	30.4
15/04/2002	15:16:35	32.4	31.4	31.2	30.5	30.7	30.5
15/04/2002	15:16:51	32.6	32.1	31.5	30.6	30.8	30.6
15/04/2002	15:17:06	32.2	31.9	31.6	30.7	30.7	30.5
15/04/2002	15:17:20	31.9	31.6	31.7	30.6	30.6	30.5
15/04/2002	15:17:35	31.7	31.5	31.7	30.6	30.5	30.3
15/04/2002	15:17:50	31.7	31.7	31.5	30.6	30.9	30.8
15/04/2002	15:18:05	33.7	32.9	32.2	31	31.2	30.8
15/04/2002	15:18:20	33.5	32.9	32.2	31.2	31.4	31.3
15/04/2002	15:18:36	33.1	32.8	32.1	31.2	31.4	31.1
15/04/2002	15:18:50	33.4	33.1	32.1	31.3	31.4	30.9
15/04/2002	15:19:05	33.5	33.4	32.6	31.3	31.3	30.9

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15/04/2002	15:19:21	33.7	33.7	33.1	31.4	31.6	31
15/04/2002	15:19:35	33.3	33.2	32.8	31.4	31.7	30.9
15/04/2002	15:19:50	36.6	34.8	33.9	31.2	31.8	31.1
15/04/2002	15:20:05	35.1	33.5	33.1	31.3	31.7	31
15/04/2002	15:20:20	33.8	32.9	32.9	31.4	31.6	31.1
15/04/2002	15:20:36	33.1	32.6	32.7	31.3	31.3	31.2
15/04/2002	15:20:51	32.8	32.4	32.6	31.4	31.2	31
15/04/2002	15:21:06	32.5	32.6	33.3	31.3	31.1	30.9
15/04/2002	15:21:20	32.2	32.2	33	31.4	31.1	30.8
15/04/2002	15:21:36	32.8	33	33.4	31.5	31.2	31
15/04/2002	15:21:51	34.6	35.4	35	31.8	31.3	31.1
15/04/2002	15:22:05	36.1	37	35.8	32.2	32	31.4
15/04/2002	15:22:20	39.5	39.1	36.2	33.2	33.8	32.5
15/04/2002	15:22:35	44.3	40.2	35.7	35.3	34	32.6
15/04/2002	15:22:51	43	40	37	34.8	34.5	32.7
15/04/2002	15:23:06	41.9	40.2	38.3	34.4	33.7	32.7
15/04/2002	15:23:21	43.3	42.8	40	34.4	34.6	33.2
15/04/2002	15:23:35	52.3	46	39.2	37.2	35.9	33.2
15/04/2002	15:23:51	71.9	49.7	38.8	44.5	36.5	33.1
15/04/2002	15:24:06	68.7	50	38.6	45.7	39.1	33.5
15/04/2002	15:24:20	67.8	50	38.3	45.2	38.2	33.7
15/04/2002	15:24:36	90.6	51.4	38.8	50.9	37.1	33.7
15/04/2002	15:24:51	100.1	47.5	39	54.9	38.8	34.7
15/04/2002	15:25:06	89.3	52.1	40.3	56.8	39.6	34.5
15/04/2002	15:25:20	81	54.6	45.1	52.4	42.6	36.8
15/04/2002	15:25:35	75.5	58.7	48.2	51.7	46.4	37.5
15/04/2002	15:25:51	72.1	62	45.6	45.9	42.7	36.9
15/04/2002	15:26:05	65.4	60.1	50.7	42.9	40.3	36.6
15/04/2002	15:26:21	94.1	57.3	47	49.7	41.6	36.7
15/04/2002	15:26:35	116.8	54	45.5	65	43.8	37.9
15/04/2002	15:26:50	105.5	58.8	50.9	62.5	43.8	38.2
15/04/2002	15:27:05	120.3	64.5	48.1	63.5	49.3	38.1
15/04/2002	15:27:21	117.7	62.5	51	65.7	56	38.2
15/04/2002	15:27:35	90.4	63.1	51.2	55.5	50	39.9
15/04/2002	15:27:50	94.5	69.6	49.9	53.9	47.2	38.8
15/04/2002	15:28:06	124.2	65.8	48.6	67.7	47.5	40.5
15/04/2002	15:28:20	123.5	72.1	48.8	73.9	47.8	40.1
15/04/2002	15:28:35	155.3	82.3	48.2	81.2	51.3	40.2
15/04/2002	15:28:50	165.2	77.3	47	88.2	53.2	41.1
15/04/2002	15:29:05	146	82.6	48.9	87	53.1	40
15/04/2002	15:29:21	151.3	95.2	53.5	86	64.4	40.8

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15/04/2002	15:29:35	149.6	98	56.8	87.8	60.5	42.2
15/04/2002	15:29:50	174.6	100.4	56.1	94.8	66.1	43.5
15/04/2002	15:30:05	194.1	88	52.1	106.5	66.8	44.5
15/04/2002	15:30:20	194.1	94	52.6	109.8	66.8	45.7
15/04/2002	15:30:35	195	90.8	52.7	116.4	66.9	45
15/04/2002	15:30:51	182.4	95.2	50.8	111.5	79.5	44.1
15/04/2002	15:31:05	193.3	102.2	55.1	104.9	80.1	43.3
15/04/2002	15:31:20	207.5	105.8	57.8	109.1	77.8	45.2
15/04/2002	15:31:35	213.5	104.6	60.2	118.1	77.4	48.1
15/04/2002	15:31:51	222.5	111.6	62.4	122	99.3	49.7
15/04/2002	15:32:05	219.5	122.1	64.2	118.9	97.4	50.1
15/04/2002	15:32:20	244.9	100.7	62.6	133.2	95.5	50.8
15/04/2002	15:32:35	250.3	118.8	62.6	138.5	96.2	53.2
15/04/2002	15:32:50	248	133.7	61.7	140	91	51.8
15/04/2002	15:33:05	260.3	128.5	59.8	144.8	89.2	51.3
15/04/2002	15:33:20	261.6	124.2	56.2	149.2	89.5	51.1
15/04/2002	15:33:35	260.5	140.7	62.9	148.8	90.2	50.5
15/04/2002	15:33:51	244.8	134.1	72	140.9	98	50
15/04/2002	15:34:06	276.3	132.2	68.4	146.8	100.3	54
15/04/2002	15:34:20	268.7	148.3	73.4	146.4	103.5	52.9
15/04/2002	15:34:35	274.9	147.5	68.2	153.2	101.4	54.8
15/04/2002	15:34:50	279.2	141.9	64.3	154.1	102.7	54.8
15/04/2002	15:35:06	286.1	128.3	61.4	161.7	101.9	53.2
15/04/2002	15:35:20	297.5	151.7	62	159.9	106.1	54.5
15/04/2002	15:35:35	273.6	165.4	72.8	157.7	104.3	54.5
15/04/2002	15:35:50	291.1	164.5	74.1	161.5	105.8	54.8
15/04/2002	15:36:05	312.6	166.1	70.1	167.5	106.4	59.6
15/04/2002	15:36:20	302.2	176.7	70.9	166.4	111.1	61.1
15/04/2002	15:36:36	268.3	158	64.9	158.5	110	55.9
15/04/2002	15:36:51	280.5	154.3	61.8	160.2	106.3	53.9
15/04/2002	15:37:05	303.9	169.8	59.9	165.1	105.1	52.8
15/04/2002	15:37:21	319.4	172.4	62.5	169	104.9	52.2
15/04/2002	15:37:35	332.5	183.1	63.6	175.3	117.5	54.2
15/04/2002	15:37:50	331.9	183.4	71.7	178.9	125.5	64
15/04/2002	15:38:06	325.3	186.7	77.1	171.5	136.6	70.7
15/04/2002	15:38:20	325.4	200.3	82.9	173.4	146.7	71.2
15/04/2002	15:38:36	328.8	203.9	86.9	179.1	148.3	71.5
15/04/2002	15:38:51	343.8	208.8	80.5	182.4	145.5	71.6
15/04/2002	15:39:05	332.6	204	78.5	185	150.4	74
15/04/2002	15:39:20	314.7	186.5	77.6	179.6	140.7	71.1
15/04/2002	15:39:35	298.7	187.6	107.9	174	150	76.7

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15/04/2002	15:39:50	308.8	192.8	114.4	165.4	154.9	72.9
15/04/2002	15:40:05	341.2	194.1	92.3	180.5	142.2	71.4
15/04/2002	15:40:21	346.5	205.5	79.7	180.5	147.5	73.8
15/04/2002	15:40:35	341.3	219	87.7	177.9	164.2	77.2
15/04/2002	15:40:50	333.4	225.9	83.1	188.1	152.8	76.8
15/04/2002	15:41:05	345.7	225.7	73.2	183.3	162.5	76.1
15/04/2002	15:41:20	346.9	229.5	73.2	194.2	170.9	74.9
15/04/2002	15:41:36	345.4	223.2	70.9	189.8	161.9	74
15/04/2002	15:41:50	335.5	214	72.2	195.1	146.8	68.3
15/04/2002	15:42:05	307.7	191	66.2	185.4	138.4	60.8
15/04/2002	15:42:21	291.2	193.6	87.8	176.8	147.9	57.4
15/04/2002	15:42:36	287.9	213.7	104	168.9	148	59.3
15/04/2002	15:42:50	333.5	221.6	92.9	172.9	159.1	66.4
15/04/2002	15:43:05	323.8	209.2	90	182.7	170.4	72.6
15/04/2002	15:43:20	328	215	76.5	181.1	157.7	71.3
15/04/2002	15:43:35	312.8	206.3	73.2	177	162.6	72.2
15/04/2002	15:43:50	326.7	199.4	74.2	183.7	153.9	75.2
15/04/2002	15:44:05	288.2	196.1	78.9	175.6	155.1	69.7
15/04/2002	15:44:21	293.8	204.4	81.7	170.6	153	74.7
15/04/2002	15:44:36	273.8	199.8	79.9	168	139.6	72.2
15/04/2002	15:44:51	262	184.1	71.2	165.7	149.4	64.1
15/04/2002	15:45:05	265.3	177.6	66.5	156.6	150.1	62
15/04/2002	15:45:20	277.1	191	74.8	159.3	143.2	63.7
15/04/2002	15:45:36	250.8	191.4	74	157.2	139.1	64.7
15/04/2002	15:45:51	231.9	180	72.3	150.4	136.5	63.4
15/04/2002	15:46:05	219.4	156.1	68.3	142.3	134.7	61
15/04/2002	15:46:20	204.6	143.2	64.7	135.6	133.3	59.1
15/04/2002	15:46:35	187.1	137.3	60.1	129.7	126.4	58.9
15/04/2002	15:46:51	165.1	126.7	60.5	122.3	117.2	61
15/04/2002	15:47:05	154.3	120.7	56.6	116.4	115.3	61.2
15/04/2002	15:47:20	144.4	117.3	61.8	108.9	108.9	64.3
15/04/2002	15:47:35	149.2	120	63.5	104.5	102.2	63.8
15/04/2002	15:47:50	136	114.2	67.4	100.1	99.6	61.1
15/04/2002	15:48:05	117.1	97.3	65.3	93.7	84.6	55.3
15/04/2002	15:48:20	112.9	97.1	61.9	88.5	79.1	50.3
15/04/2002	15:48:35	113.3	101.7	59.4	87.3	82.8	50.7
15/04/2002	15:48:51	111.9	98.9	58.1	84.9	79.7	52
15/04/2002	15:49:05	106	93.7	55.8	85.2	80.5	52.1
15/04/2002	15:49:20	96.4	84	59	81.2	78.2	51.7
15/04/2002	15:49:35	90.5	79.9	55	77.7	72	47.8
15/04/2002	15:49:50	89.3	73.5	54.4	74.1	68.9	46

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15/04/2002	15:50:05	77.8	64.9	52.2	69.1	60.6	45.4
15/04/2002	15:50:21	76.2	63.4	51.3	64	54.3	43.7
15/04/2002	15:50:35	82.6	67.2	51	64.2	54.2	44.9
15/04/2002	15:50:51	84.8	71.4	48.9	65.8	52.5	44.5

Table A.23 Temperature Results on Point 9

Date	Clock	D036	D037	D038
15/04/2002	15:10:05	29.5	29.6	29.6
15/04/2002	15:10:21	29.4	29.5	29.6
15/04/2002	15:10:36	29.4	29.5	29.6
15/04/2002	15:10:51	29.3	29.4	29.5
15/04/2002	15:11:05	29.4	29.4	29.5
15/04/2002	15:11:20	29.4	29.5	29.5
15/04/2002	15:11:36	29.5	29.5	29.5
15/04/2002	15:11:50	29.5	29.6	29.6
15/04/2002	15:12:06	29.6	29.6	29.6
15/04/2002	15:12:20	29.6	29.6	29.6
15/04/2002	15:12:36	29.6	29.6	29.6
15/04/2002	15:12:51	29.6	29.6	29.6
15/04/2002	15:13:05	29.6	29.6	29.6
15/04/2002	15:13:20	29.9	29.6	29.7
15/04/2002	15:13:35	30.6	30.2	30.2
15/04/2002	15:13:51	31.1	30.7	30.7
15/04/2002	15:14:05	31	30.7	30.6
15/04/2002	15:14:20	30.9	30.7	30.6
15/04/2002	15:14:36	30.7	30.5	30.4
15/04/2002	15:14:50	30.8	30.4	30.4
15/04/2002	15:15:06	30.7	30.5	30.4
15/04/2002	15:15:20	30.8	30.6	30.5
15/04/2002	15:15:35	30.6	30.4	30.2
15/04/2002	15:15:50	30.3	30.2	30.1
15/04/2002	15:16:06	30.2	30.1	30.1
15/04/2002	15:16:21	30.5	30.3	30.2
15/04/2002	15:16:35	30.8	30.5	30.4
15/04/2002	15:16:51	30.8	30.7	30.5
15/04/2002	15:17:06	30.8	30.6	30.4
15/04/2002	15:17:20	30.8	30.6	30.5
15/04/2002	15:17:35	30.9	30.6	30.6
15/04/2002	15:17:50	30.9	30.7	30.6
15/04/2002	15:18:05	30.9	30.8	30.8
15/04/2002	15:18:20	30.8	30.8	30.8
15/04/2002	15:18:36	30.9	30.7	30.6
15/04/2002	15:18:50	31.1	30.8	30.6
15/04/2002	15:19:05	31.1	30.8	30.6

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15/04/2002	15:19:21	31.2	30.8	30.6
15/04/2002	15:19:35	31.1	30.7	30.5
15/04/2002	15:19:50	30.9	30.7	30.4
15/04/2002	15:20:05	31.2	30.8	30.6
15/04/2002	15:20:20	31.6	31.3	31
15/04/2002	15:20:36	31.6	31.1	30.9
15/04/2002	15:20:51	31.8	31.4	31.2
15/04/2002	15:21:06	31.7	31.4	31.2
15/04/2002	15:21:20	32.1	31.8	31.4
15/04/2002	15:21:36	32.1	31.9	31.5
15/04/2002	15:21:51	32.6	32	31.7
15/04/2002	15:22:05	33.1	32.5	31.7
15/04/2002	15:22:20	33.4	32.8	32
15/04/2002	15:22:35	34.1	32.9	31.9
15/04/2002	15:22:51	34.3	33.3	32.2
15/04/2002	15:23:06	34.8	33.4	32.2
15/04/2002	15:23:21	34.7	33.2	32.1
15/04/2002	15:23:35	34.4	33.1	32.5
15/04/2002	15:23:51	41.5	35.5	32.7
15/04/2002	15:24:06	43.3	37.2	33.1
15/04/2002	15:24:20	38.7	35.9	33.3
15/04/2002	15:24:36	43.4	36.7	33.7
15/04/2002	15:24:51	53.6	40.7	34.2
15/04/2002	15:25:06	55	42.3	34.5
15/04/2002	15:25:20	47.5	40.6	35.1
15/04/2002	15:25:35	49.1	40.9	36.6
15/04/2002	15:25:51	41.7	38.6	36.2
15/04/2002	15:26:05	40.6	38.3	36.4
15/04/2002	15:26:21	43.7	38.4	35.9
15/04/2002	15:26:35	58.5	42.9	36.9
15/04/2002	15:26:50	61.7	44.3	37.4
15/04/2002	15:27:05	58.3	45.5	38.3
15/04/2002	15:27:21	65.3	48.8	37.8
15/04/2002	15:27:35	52.3	45.8	39.6
15/04/2002	15:27:50	48.4	43.3	38.3
15/04/2002	15:28:06	60	45.4	39.3
15/04/2002	15:28:20	69.9	48.8	41
15/04/2002	15:28:35	75.3	55.7	39.8
15/04/2002	15:28:50	85.3	59.7	41.1
15/04/2002	15:29:05	84.7	57.2	41
15/04/2002	15:29:21	85.6	64	42.3

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15/04/2002	15:29:35	77.9	61	43.1
15/04/2002	15:29:50	90.5	65.7	46.1
15/04/2002	15:30:05	101.3	69.9	46.9
15/04/2002	15:30:20	103.5	69.8	45.6
15/04/2002	15:30:35	106.4	74.3	47.6
15/04/2002	15:30:51	103.3	71	43.7
15/04/2002	15:31:05	101.7	70.4	43.9
15/04/2002	15:31:20	110.9	73.8	43.5
15/04/2002	15:31:35	121.4	78.5	47.3
15/04/2002	15:31:51	123.3	85.8	48.6
15/04/2002	15:32:05	119.5	87.7	48.5
15/04/2002	15:32:20	132.9	94	50.1
15/04/2002	15:32:35	133.9	93.8	49.3
15/04/2002	15:32:50	130.7	92.9	51.4
15/04/2002	15:33:05	128.9	97.5	48.9
15/04/2002	15:33:20	130.5	96.9	50.7
15/04/2002	15:33:35	135.9	96.2	49.3
15/04/2002	15:33:51	133.3	100.9	49
15/04/2002	15:34:06	144.2	107.4	53.1
15/04/2002	15:34:20	144.4	106.8	51.6
15/04/2002	15:34:35	145.4	109.1	50.4
15/04/2002	15:34:50	140.9	105.1	50.3
15/04/2002	15:35:06	154.9	109.4	47.6
15/04/2002	15:35:20	151.3	110.1	50.2
15/04/2002	15:35:35	150.9	111.8	51.5
15/04/2002	15:35:50	158.8	117.2	51.3
15/04/2002	15:36:05	164.7	118.5	55.3
15/04/2002	15:36:20	166.1	118	59.3
15/04/2002	15:36:36	150.3	116.9	56.2
15/04/2002	15:36:51	148.1	116.2	51.9
15/04/2002	15:37:05	152.1	116.4	53.5
15/04/2002	15:37:21	162.6	120.7	59.1
15/04/2002	15:37:35	173	119.2	60.5
15/04/2002	15:37:50	173.2	131.1	61.7
15/04/2002	15:38:06	180.1	138.6	66.3
15/04/2002	15:38:20	172.2	135.3	66.2
15/04/2002	15:38:36	182.1	144.2	66.6
15/04/2002	15:38:51	179.1	146.1	68.5
15/04/2002	15:39:05	181.7	144.5	71.1
15/04/2002	15:39:20	177.9	138.4	68.4
15/04/2002	15:39:35	179.9	139.2	69.5

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15/04/2002	15:39:50	165	135.8	76.7
15/04/2002	15:40:05	177.1	137	73.8
15/04/2002	15:40:21	190.6	143.9	74.7
15/04/2002	15:40:35	185.1	150.7	74.6
15/04/2002	15:40:50	184.5	152.1	72.7
15/04/2002	15:41:05	181.8	149.3	74.8
15/04/2002	15:41:20	189.2	150.4	69.8
15/04/2002	15:41:36	180.1	150.9	68.6
15/04/2002	15:41:50	177.7	150.2	62.5
15/04/2002	15:42:05	170	140.5	57.3
15/04/2002	15:42:21	168.7	137.5	56.2
15/04/2002	15:42:36	161.2	135.4	60.4
15/04/2002	15:42:50	181.1	149.4	73.1
15/04/2002	15:43:05	184.6	152.2	73
15/04/2002	15:43:20	181	148.9	70.1
15/04/2002	15:43:35	180.7	149.7	71.3
15/04/2002	15:43:50	186.5	155.5	68.5
15/04/2002	15:44:05	175.1	150.1	67.4
15/04/2002	15:44:21	170.8	147.9	69.6
15/04/2002	15:44:36	163.4	146.6	64.4
15/04/2002	15:44:51	158.2	139.7	56.8
15/04/2002	15:45:05	152	138.3	53
15/04/2002	15:45:20	161.1	136.8	59.6
15/04/2002	15:45:36	158.4	139.1	61.2
15/04/2002	15:45:51	148.7	135	57.4
15/04/2002	15:46:05	144.3	128.8	56.2
15/04/2002	15:46:20	135.5	120.9	61.2
15/04/2002	15:46:35	133.7	118.6	59.9
15/04/2002	15:46:51	122.4	113.7	60.9
15/04/2002	15:47:05	117.1	109.1	59.9
15/04/2002	15:47:20	108.7	102.5	58.6
15/04/2002	15:47:35	106.6	98.4	59.3
15/04/2002	15:47:50	103.2	97.2	57.6
15/04/2002	15:48:05	96.3	89.2	54.8
15/04/2002	15:48:20	89.4	82.8	52.1
15/04/2002	15:48:35	89.6	82.1	52.9
15/04/2002	15:48:51	89.5	82.9	54
15/04/2002	15:49:05	88.3	81	51.8
15/04/2002	15:49:20	84.3	77.7	50.8
15/04/2002	15:49:35	78.7	70.2	47.6
15/04/2002	15:49:50	76.7	69.3	45.9

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15/04/2002	15:50:05	61.4	58.4	45
15/04/2002	15:50:21	52.9	50.4	43.5
15/04/2002	15:50:35	59.6	52.2	43.9
15/04/2002	15:50:51	64.4	54.7	44.6

APPENDIX A

A.5 Gas Concentration Results for CF002, White-Block Configuration

Table A.24 Gas Concentrations Measurement Results on Point 1

Date	Clock	CO ₂ (ppm)	CO (ppm)	TVOC ref	H ₂ O (mg/m ³)
				Toluene	
15/04/2002	15:10:46	691.280029	1.6787	12.426	21194
15/04/2002	15:12:37	689.559998	1.7771	11.919	21130
15/04/2002	15:14:28	691.419983	1.5451	12.55	21323
15/04/2002	15:16:19	693.580017	1.6266	13.154	21073
15/04/2002	15:18:09	693.280029	1.6353	12.592	21172
15/04/2002	15:20:10	697.650024	1.6362	12.496	21038
15/04/2002	15:22:01	685.359985	1.6393	12.19	21010
15/04/2002	15:23:52	690.530029	1.4575	12.418	21114
15/04/2002	15:25:42	720.47998	1.6703	12.32	20904
15/04/2002	15:27:33	739.049988	2.099	12.251	20860
15/04/2002	15:29:24	743.150024	2.2367	12.561	20866
15/04/2002	15:31:30	910.650024	3.3692	13.953	21133
15/04/2002	15:33:21	1679.699951	8.4984	18.969	21593
15/04/2002	15:35:11	1269.900024	7.0233	16.141001	21388
15/04/2002	15:37:02	1811.5	9.1816	18.171	21656
15/04/2002	15:38:53	1435.599976	6.4379	15.69	21493
15/04/2002	15:40:54	1168.099976	4.5091	14.212	21255
15/04/2002	15:42:44	1014.200012	3.2215	13.456	20906
15/04/2002	15:44:35	931.830017	3.0508	13.041	20940
15/04/2002	15:46:26	977.280029	2.6699	12.813	20935
15/04/2002	15:48:17	799.909973	5.1026	13.509	20885
15/04/2002	15:50:17	711.859985	3.2348	12.906	20844

Table A.25 Gas Concentrations Measurement Results on Point 5

Date	Clock	CO ₂ (ppm)	CO (ppm)	TVOC ref	H ₂ O
				Toluene	(mg/m ³)
15/04/2002	15:09:51	688.679993	1.6616	12.448	21119
15/04/2002	15:11:42	695.47998	1.6696	12.417	21263
15/04/2002	15:13:32	695.22998	1.6148	12.405	21239
15/04/2002	15:15:23	700.669983	1.7328	14.459	21154
15/04/2002	15:17:14	692.150024	1.4448	12.031	21036
15/04/2002	15:19:05	704.219971	1.5992	12.565	21101
15/04/2002	15:21:06	691.5	1.7116	11.993	20876
15/04/2002	15:22:56	691.780029	1.5878	12.315	21080
15/04/2002	15:24:47	697.409973	1.6968	12.449	20957

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15/04/2002	15:26:38	980.419983	4.0839	16.113001	20954
15/04/2002	15:28:29	783.25	2.3067	12.817	20916
15/04/2002	15:30:35	1115	5.3412	15.54	21198
15/04/2002	15:32:25	800.909973	2.2131	13.16	21141
15/04/2002	15:34:16	843.049988	2.7789	13.054	21224
15/04/2002	15:36:07	1057.199951	4.993	14.622	21389
15/04/2002	15:37:58	919.679993	3.3791	13.702	21347
15/04/2002	15:39:58	1038.300049	3.8781	13.55	21050
15/04/2002	15:41:49	1992.900024	9.103	17.323	21684
15/04/2002	15:43:40	856.619995	2.5003	12.765	20954
15/04/2002	15:45:31	1031.099976	3.171	13.274	20889
15/04/2002	15:47:21	709.22998	1.8363	11.828	20818
15/04/2002	15:49:12	984.599976	31	24.33	21365
15/04/2002	15:51:13	735.609985	7.3578	13.867	20927

APPENDIX B FDS2 MODELLING RESULTS

NIST Smokeview 2.0 - December 9, 2001

Figure B.1 The FDS2 Simulation Result of CF001 Test
Flame of Fire at 1200 sec

APPENDIX B

NIST Smokeview 2.0 - December 9, 2001, CFTM007_1200_00.q

Figure B.2 The FDS2 Simulation Result of CF001 Test
Gas Temperature Contour at 1200sec

APPENDIX B

Figure B.3 The FDS2 Simulation Result of CF001 Test
Gas Flow at 1200sec

NIST Smokeview 2.0 - December 9, 2001

Figure B.4 The FDS2 Simulation Result of CF002 Test
Flame at 1200sec

APPENDIX B

NIST Smokeview 2.0 - December 9, 2001, CFTM008_1200_01.q

Figure B.5 The FDS2 Simulation Result of CF002 Test
Gas Temperature Contour at 1200sec

APPENDIX B

Figure B.6 The FDS2 Simulation Result of CF002 Test
Gas Flow at 1200sec