Building energy saving by active simplified CFD-based model predictive control and passive earth-sheltering technique

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**NANYANG
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SINGAPORE

**BUILDING ENERGY SAVING BY ACTIVE SIMPLIFIED
CFD-BASED MODEL PREDICTIVE CONTROL AND
PASSIVE EARTH-SHELTERING TECHNIQUE**

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SCHOOL OF MECHANICAL AND AEROSPACE ENGINEERING

2019

**BUILDING ENERGY SAVING BY ACTIVE SIMPLIFIED CFD-
BASED MODEL PREDICTIVE CONTROL AND PASSIVE
EARTH-SHELTERING TECHNIQUE**

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A thesis submitted to the Nanyang Technological University
in partial fulfilment of the requirement for the degree of
Doctor of Philosophy

2019

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The contributions of the co-authors are as follows:

- I, Xiaoli Zhou, conceived of the original idea, performed the computations, and wrote the manuscript draft.
- A/Prof Hua Li suggested the initial work direction and edited the manuscript draft.
- Prof Yeng Chai Soh supervised the work and commented on the manuscript.
- Dr Chaoyang Jiang assisted in the development of control algorithm.

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Summary

Due to the increasing energy consumption and environmental impact caused by the building sector, the present research work mainly focuses on the improvement of overall energy efficiency in buildings by both active and passive strategies, for example, the model predictive control (MPC) and earth-sheltering respectively.

As an advanced active technique, the MPC requires an accurate internal model to predict the system behavior and computes the control inputs by minimizing the cost function, while Computational Fluid Dynamics (CFD) describes well the internal dynamics of imperfectly mixed fluids. Therefore, it is a promising way to achieve energy saving by integrating CFD into real-time MPC. However, the literature review reveals that no study has been conducted on directly coupling the CFD model with the control system, due to the CFD high nonlinearity and enormous computational cost. In this thesis, a novel strategy is developed, called Simplified CFD based MPC (SCFD*b*MPC), for the real-time optimization of thermal performance in the indoor environment. A CFD model is simplified firstly to capture the thermal behavior of indoor environment with desirable computational cost. The simplified CFD model is then verified using the commercial CFD code FLUENT, and finally integrated into the MPC algorithm to form SCFD*b*MPC system via successive linearization technique. Finally, the effects of key parameters are investigated on the control performance of the SCFD*b*MPC system, including the inlet and outlet locations, multiple outlets, and occupant movement. It is found that the SCFD*b*MPC system is an efficient workable platform for optimal control and dynamic prediction of thermal distributions in indoor environment, which adapts well to the time-varying set points, various boundary conditions, and occupant movement.

Apart from the active design strategy of MPC, the earth-sheltered building, as one of passive cooling techniques, could also be an efficient solution for sustainable development of building, characterized by solar heat reduction, stable soil temperature, and natural thermal insulation. However, few studies have paid attention to its CFD and energy modellings with consideration of the heat stored in soil, as well as to develop the optimal control system adapted with the time-varying temperature of the surrounding soil for the earth-sheltered building. Therefore, the second achievement in this thesis is made through the CFD and CFD-coupled energy modelling as well as full-CFD-coupled MPC design for earth-sheltered buildings. A transient CFD model is proposed firstly to analyze the heat flux transferred from soil to earth-sheltered building. Subsequently, the CFD model is coupled with energy simulation for prediction of the energy demand in earth-sheltered buildings. Furthermore, a predictive model is developed to properly represent the dynamic thermal behavior of the earth-sheltered building. According to the present predictive model and CFD simulation, a novel co-simulation optimal strategy is proposed for the thermal control of earth-sheltered buildings, which adapts well to the time-varying soil temperature. The proposed CFD model is then validated by published works. In addition, the influence of critical parameters is evaluated on the thermal and energy performance of earth-sheltered building, such as the depth, soil thermal property, temperature set point, envelope material, and climatic condition. Finally, the co-simulation optimal strategy is performed for case studies of earth-sheltered buildings, and it is thus concluded that the co-simulation optimal strategy is an efficient platform for the thermal control and energy efficiency of earth-sheltered building.

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Chapter 1

Introduction

This is the first chapter of the present thesis, consisting of several sections, namely the background, motivation, objectives, and outline. Section 1.1 introduces the background of global building energy consumption, followed by the overview of active control and passive design approaches for building energy efficiency. The motivation and objectives of the present thesis are elaborated in Section 1.2. Finally, the thesis organization is presented in Section 1.3.

1.1 Background

1.1.1 Energy consumption in buildings

With increasing energy consumption, more and more attention is given to reduce the carbon footprint in the world. Final energy consumption is usually classified into three main categories, namely industry, transport, and building. In Europe, the energy consumption of building accounts for 39% of the total final energy use, more extensive than those of industry (28%) and transport (32%) [1]. Similarly, the building energy consumption (BEC) contributes 40% of total energy consumption in the USA [2], indicating that the building sector is always one of the largest energy end users in developed countries. The upward trend in BEC continues in future, due to the economic development and population growth. Among the various building services, the energy demand of heating, ventilating, and air-conditioning (HVAC) system is highest accounting for nearly 50% of the BEC, and approximately 20% of total energy consumption in developed countries [3]. In particular, a substantial amount of energy

in Singapore is consumed by the all-year air-conditioning for thermal comfort, owing to the humid and hot tropical climate [4]. Therefore, the improvement of building services, especially higher efficiency of air-conditioning, is crucial to address the global energy-supply issue.

Furthermore, the increasing energy consumption results in broad concerns over massive environmental issues, such as the ozonosphere depletion and global warming. As reported by International Energy Agency [5], the global average concentration of CO₂ has grown by about 40% during the last two decades, with an annual average increase of 1.7 %. As illustrated in Figure 1.1 [6], the upward trend is observed on CO₂ emissions of end-use sectors, and the building contributes more than one-third of global greenhouse gas emissions. Therefore, it is necessary for designers and researchers to develop highly energy-efficient systems for buildings.

Figure 1.1. Trend of CO₂ emissions by end-use sectors [6].

1.1.2 Strategies for building energy efficiency

In order to improve the energy efficiency and thermal comfort in buildings, numerous technologies are developed and mainly categorized into two groups, namely the active and passive design strategies [7]. Active design strategies usually refer to the optimization of building facilities and services, including the HVAC system and

electrical lighting, whereas, passive design strategies aim to improve the building envelope elements and make use of the natural energy resources, such as natural ventilation, daylighting, and geothermal energy [8].

As the HVAC system becomes the major energy consumption in buildings [2], researchers and engineers pay much attention to its optimization strategies. One efficient method is optimal control, defined as a way to monitor and modify conditions that affect system performance dynamically [9]. It is promising to develop and implement efficient control techniques in buildings for their unique advantages on energy conservation and human comfort. In particular, the Model Predictive Control (MPC) gains widespread popularity, because it allows integration of constraint handling, disturbance rejection, real-time control of slow movement, and energy saving approaches into the controller formulation [10].

Moreover, the passive design strategy of building becomes a research hot point nowadays, as a feasible alternative solution to the world energy crisis and associated environmental concern [11]. The earth-sheltering technique appears to be a promising passive energy strategy, by making use of the thermal mass and annual thermal stability of earth material [12]. The earth-sheltered housing has long been adopted by humankind for shelter, safety, and thermal comfort. In the modern era, the earth-sheltered building is described as architectures utilising the thermal mass of earth against building envelope for maintaining a stable indoor air temperature and reducing heat loss over the seasons [13]. Except for the energy conservation as proved by a number of studies, the earth-sheltered building also offers other benefits, such as solar heat reduction, land preservation, and noise cancellation [12]. Therefore, the earth-sheltered building, as an

efficient passive design strategy, shows great potential in the energy saving of HVAC system in buildings.

1.2 Motivation and objectives

Due to the increasing energy consumption and environmental impact caused by the building sector, the present research work mainly focuses on the improvement of overall energy efficiency in buildings by both active and passive strategies, for example, the MPC and earth-sheltering respectively.

As an advanced active design technique, the MPC adopts an internal model to predict the system behavior and computes the control inputs by minimizing the cost function [14], it may help to reduce the energy load of air-conditioning substantially with desirable thermal comfort [15], provided that the internal model captures the system behavior precisely. In the most of current building modellings however, a much simplified “well-mixed” assumption is adopted [16], namely the uniform distributive air temperature with fixed air-flow pattern, but it fails to characterize the real ventilation performance in buildings, where the air is usually imperfectly mixed. As well known, CFD describes well the internal dynamics of heat and mass transfer for imperfectly mixed fluids, based on the conservation laws [17]. Therefore, combining CFD with real-time MPC becomes a promising and innovative way to save energy significantly and achieve thermal comfort in buildings simultaneously. However, the literature review shows that no study was conducted on directly coupling the CFD model with the control system, due to the CFD high nonlinearity and enormous computational cost. It might help to perform the CFD coupled with control strategy, if the disadvantages of CFD model are overcome.

Moreover, besides the active design strategy, the earth-sheltered building, as one of passive cooling techniques, could also be an efficient solution for building energy efficiency [18]. However, the heat transferred from soil to earth-sheltered building is complicated, depending on the depth below the ground surface, soil properties such as thermal properties and humidity, building envelope materials, and ventilation system. Therefore, a complete thermal dynamic analysis by CFD simulation is required to analyze the heat across the envelope of earth-sheltered building. Furthermore, in the current modelling of energy consumption and control system, the temperature of soil is often assumed constant and hence the temperature variation due to the thermal storage capacity of soil is neglected. It is thus essential to couple CFD with energy simulation (ES) and optimal control for the energy efficiency of earth-sheltered building, by considering the temperature fluctuation of the surrounding soil.

Therefore, this thesis aims to develop a platform to couple a simplified CFD model with the real-time control system for the dynamic optimization of temperature distribution in indoor environment, in order to efficiently reduce the energy use and improve the thermal comfort simultaneously. In addition, regarding the earth-sheltered building, through CFD and CFD-coupled energy modelling analysis, the influence of critical parameters is evaluated on the thermal and energy performance of the building. Finally, an optimal strategy coupling full CFD with MPC is proposed for the thermal control of earth-sheltered building, and its performance is analyzed. The specific objectives and the corresponding scopes are summarized below.

- Development of a novel strategy of Simplified Computational Fluid Dynamics based Model Predictive Control (SCFD δ MPC) for real-time optimization of thermal performance in indoor environment. A CFD model is simplified based on governing equations and rational assumptions to capture the thermal

behaviour of indoor environment with desirable computational cost. The simplified CFD model is verified with its full CFD counterpart by ANSYS/FLUENT, and integrated into the MPC algorithm to form the SCFDbMPC system using successive linearization technique. The developed SCFDbMPC system is verified by FLUENT simulation, and then extended to study the effects of inlet and outlet locations, multiple outlets, and occupant movement on the real-time control performance of SCFDbMPC system in indoor environment.

- CFD and CFD-coupled energy modelling analysis for the thermal and energy performance of earth-sheltered building. A transient two-dimensional (2D) CFD model is built up to analyze the heat transferred from soil to earth-sheltered building and validated by published works. In addition, the energy modelling of earth-sheltered building is presented by coupling the developed CFD model with ES. Based on the CFD and energy modelling analysis, the influence of critical parameters, namely the depth, soil thermal property, set point, envelope material, and climatic condition, is evaluated on the thermal and energy performance of earth-sheltered building.
- Full-CFD-coupled MPC design for optimization of thermal performance in earth-sheltered building. A predictive model is developed to represent the thermal behaviour of earth-sheltered building properly. According to the above CFD and predictive models, a novel co-simulation optimal strategy is proposed for the thermal control of earth-sheltered building, which adapts well with the time-varying temperature of surrounding soil. Finally, case studies are carried out to examine the performance of the co-simulation strategy for the optimization of thermal performance in earth-sheltered building.

1.3 Thesis outline

This thesis is comprised of five chapters, and they are organized further as follows.

Chapter 1 generally introduces the background of global energy consumption in buildings, followed by the overview of active and passive design techniques for building energy efficiency. The motivation, objective, and scope of the thesis are also presented in this chapter.

Chapter 2 reviews the published works on the thermal modelling and control strategies for indoor environment and earth-sheltered building. The classification of building models is presented, followed by the mathematical models and critical parameters for the modelling of earth-sheltered building. In addition, control techniques are thoroughly reviewed and discussed for the indoor environment and earth-sheltered building as well as internal models of MPC.

Chapter 3 develops a novel strategy called SCFD*b*MPC for optimization of thermal performance in indoor environment. Firstly, based on the Navier-Stokes equations, a CFD model is simplified for the simulation of indoor environment, in order to significantly reduce computational cost with acceptable numerical accuracy. The simplified CFD model is verified with its full CFD counterpart, and then integrated into the MPC algorithm to form the SCFD*b*MPC system using successive linearization technique. After the verification of SCFD*b*MPC system, some case studies are conducted on the optimal control of thermal performance in indoor environment.

Chapter 4 presents the CFD and CFD-coupled energy modelling as well as full-CFD-coupled MPC design for earth-sheltered building. A transient 2D CFD model is proposed to analyze the heat flux transferred from soil to earth-sheltered building. The developed 2D CFD model is then validated by relevant published works. Based on the

CFD modelling analysis, the influence of key parameters is evaluated on the thermal performance of earth-sheltered building. Subsequently, the energy modelling for earth-sheltered building is presented by coupling the developed CFD model with ES, followed by case studies on the building energy performance. Furthermore, a predictive model is developed to properly represent the dynamic thermal behavior of the earth-sheltered building. According to the present predictive and CFD models, a novel co-simulation optimal strategy is proposed for the thermal control of earth-sheltered building, which adapts well to the time-varying soil temperature. Finally, the performance of the optimal control strategy is thoroughly evaluated for the earth-sheltered building.

Chapter 5 draws conclusions from the present work, and recommends the possible future work on the improvement of SCFD $\bar{b}$ MPC system as well as the influence of humidity gain by seepage and phase change material (PCM) on the thermal and energy performance of earth-sheltered buildings.

Chapter 2

Literature Review

In this chapter, a literature review is conducted systematically on the thermal modelling and control strategies of indoor environment and earth-sheltered building. Section 2.1 introduces the models for visualization of thermal performance in building, followed by mathematical models and key influential factors for the modelling of earth-sheltered building. Section 2.2 focuses on the control strategies for indoor environment and earth-sheltered building, as well as the internal models of MPC. At last, Section 2.3 presents a summary of research gaps as possible contributions arising from the present thesis.

2.1 Thermal modelling of indoor environment and earth-sheltered building

2.1.1 Thermal modelling of indoor environment

For small spaces in buildings, it is often reasonable for the “well-mixed” assumption, namely the uniform distributive air temperature with fixed air-flow pattern. However, it may not hold well for the assessment of the ventilation performance for large spaces. To address this issue, it is critically important to adopt suitable tools to predict the ventilation performance such as the temperature and air distributions. In general, most widely used models for visualization of the indoor environment are categorized into five groups, namely the analytical model, full- and small-scale experimental models, empirical model, and CFD model [16].

2.1.1.1 Analytical model

Analytical model is derived from elemental equations of conservation laws for mass, momentum and energy. As well known, an analytical solution provides a perfect

closed-form expression for the dependent variable consecutively all over the computational domain, but it is always difficult to obtain analytical solutions for general partial differential equations. Especially it is impossible for Navier-Stokes equations. Generally, the geometry and boundary conditions are simplified to achieve solutions for analytical models. In the study of Duan and Jing [19], a transient model was introduced to characterize the displacement ventilation performance in the building shown in Figure 2.1. The temperature variation of the solar collecting wall (SCW) T_y as a function of time t was given by

$$\frac{dT_y}{dt} = \frac{1}{\rho_m C_m L} \left[\alpha \tau' I + h_o (T_o - T_y) + h_y \left(\left(1 + \frac{g'}{g}\right) T_o - T_y \right) \right] \quad (2.1)$$

where T_o is the outdoor temperature, L , ρ_m , and C_m are the thickness, density, and heat capacity of the SCW respectively, h_o is the coefficient of heat convection between SCW and outdoor air, h_y is the coefficient of heat convection between indoor air and SCW, α is the solar absorptivity of solar collecting wall, τ' the solar transmissivity of the glazing, I the solar radiation intensity, g the gravity and g' the reduced gravity.

Figure 2.1. Schematic of displacement ventilation [19].

Recent applications of the analytical model are introduced as follows. Davidovic *et al.* [20] developed analytical equations to predict the ventilation rate in ventilated and screened wall system and laid a strong foundation for the evaluation of convective

drying performance. Dehghan *et al.* [21] investigated the effect of wind speed and direction on the ventilation capacity of one-sided wind-catcher models by analytical modelling. Schulze and Eicker [22] simulated the steady-state ventilation air flow rates in the natural ventilation system for different boundary conditions using both analytical and airflow network methods. Xiong *et al.* [23] conducted analytical modelling for the emissive and absorptive behaviors of volatile organic compounds and formaldehyde in the building material of single layer.

Above reviews demonstrated that the analytical method is still widely used as a desirable tool for visualization of indoor environment due to its easiness and richness in physical significance, although it is often not applicable for complicated cases.

2.1.1.2 Empirical model

Empirical model is built from the energy, mass, and chemical species conservation equations which are similar to the analytical models. It usually adopts more approximations or assumptions for its coefficients sometimes from experience or experiment, compared with the analytical models. For example, Wang and Chen [24] developed a novel empirical model for the computation of the mean and fluctuating ventilation rates under the conditions of single-sided eddy penetration and pulsating flow, the wind-driven natural ventilation system is shown in Figure 2.2. The mean and fluctuating ventilation rates were given by

$$\bar{Q} = \frac{C_d l \sqrt{C_p} \int_{z_0}^h \sqrt{z^{2/7} - z_0^{2/7}} dz}{z_{ref}^{1/7}} \bar{U} \quad (2.2)$$

$$\sigma_q = \sqrt{\sigma_{qe}^2 + \sigma_{qp}^2} \quad (2.3)$$

where $\bar{Q}$ is mean ventilation rate, C_p pressure coefficient, C_d discharge coefficient, l opening width, z position, z_0 the position of neutral plane, z_{ref} the position at 10 m, $\bar{U}$

mean speed, σ_q fluctuating ventilation rate, σ_{qe} and σ_{qp} are the root mean squares for eddy penetration and pulsating flow, respectively.

Figure 2.2. Schematic of wind-driven ventilation [24].

Recent applications are introduced in the following examples. Using the empirical approach, Di Perna *et al.* [25] built a model to estimate the real-time airflow rates in a subway station where costly and intrusive measuring techniques were not available. In the research of Homod *et al.* [26], utilizing an empirical equation called residential load factor, the heating and cooling loads were computed based on the outdoor and indoor temperature. Schauburger *et al.* [27] used an empirical model to calculate the odor emissive rate from barns and derived a standardized odor emissive coefficient. These applications imply that the empirical method is an effectively low-cost tool for ventilation designers to predict ventilation performance but has contributed only a bit to the research literature in recent years.

2.1.1.3 Full- and small-scale experimental models

In general, a full-scale experimental setup is necessary for the experimental study of ventilation performance of buildings or rooms at full size, while the small-scale experimental model is also workable for a reduced-scale building or room. Each has both weakness and strength. The full-scale method provides the most actual visualization of thermal environment in buildings, but it is usually very costly and time-

consuming. However, a small-scale experimental model is a cost-effective approach but often challenging to fulfill the practical requirements for highly complex problems.

Figure 2.3. Setup of a small-scale experimental model [28].

As illustrated in Figure 2.3, Bangalee *et al.* [28] constructed a small-scale experimental cubic model to analyze the flow distribution of fluid-driven natural cross-ventilation, the results showed a satisfactory agreement with that obtained from computation and hence provided a workable tool for CFD users to validate numerical approaches in future. Lou *et al.* [29] conducted wind-tunnel experiments to validate the proposed zonal approach, the wind pressures acted on three surfaces of the corridor double-skin façade (DSF) of the building were investigated, the results showed a good agreement. In the research of Hoof *et al.* [30], the transitional flow in a ventilated enclosure was visualized and analyzed using particle image velocimetry technique, and the high-quality experimental results showed a good potential to validate numerical simulations.

Figure 2.4. Front view of the experimental building [31].

One example of full-scale experimental model is shown in Figure 2.4, Caciolo *et al.* measured the single-sided ventilation performance by full-scale experiments and compared the outputs with the results from two turbulence models (RANS and LES), and the comparison indicated that LES provided relatively accurate results in most cases compared with RANS. A four-level building with western atrium was utilized for the experimental study conducted by Ray *et al.* [32] to validate certain CFD turbulence models, and the approach using neutrally buoyant helium bubbles was found to visualize the airflow effectively.

These applications of the small- and full-scale experimental models imply a similar trend that they both are mainly applied to the validation of numerical models, especially CFD models.

2.1.1.4 Multi-zone model

Figure 2.5. Schematic of multi-zone model [33].

Given reliable input data, the multi-zone airflow modelling, as shown in Figure 2.5, is a desirable tool for the prediction of air exchange rates and airflow structures in buildings and is also capable of giving valuable insights into the smoke control, ventilation performance, energy utilization, and indoor environmental quality [33]. On the basis of conservation laws of energy, mass, and chemical-species, the multi-zone

model neglects the momentum effect with the assumption of still or quiescent indoor air and uniform temperature for each zone.

Ng *et al.* [34] developed several reference building models using the multi-zone ventilation and indoor environmental quality analysis program CONTAM to calculate the airflow and analyze the indoor air quality with physical significance. Yang and Wang [35] built a multi-zone model by partitioning the whole space into several zones to develop an effective scheme for energy management, also a novel building control was proposed by coupling an intelligent optimizer with the multi-agent control strategy to fulfill the thermal-comfort demand with high energy efficiency. Rim *et al.* [36] adopted a multi-zone contaminant transport and ventilation model to study the movement of size-resolved outdoor ultrafine particle in a test building under different ventilation scenarios.

The main advantage of multi-zone model is the capability to give deep insights into the building behavior over a large time period with a small computational cost. Therefore, it is considered a desirable technique to obtain valued data for the visualization of building ventilation performance comprehensively. However, it is not available to study the local effect of a pollutant or heat source due to its simplification.

2.1.1.5 Zonal model

The zonal model refers to the first level of simplification of the CFD methodology, by dividing a computational domain into limited amounts of cells. The non-uniform temperature distribution is thus computed in every cell which represents a small part of the space.

Abadie *et al.* [37] proposed a new zonal model to characterized the forced convection in indoor environment, which greatly improved the prediction of the air pattern with

less computational efforts, compared with fast fluid dynamic and coarse-grid CFD. Lou *et al.* [29] used the zonal approach to investigate the wind pressure on a corridor DSF of a test building, the zonal method was validated to be a desirable technique for predicting the DSF performance by experimental data. A novel zonal method, called velocity propagating zonal (VEPZO) model, that allows the evaluation of many different configurations was proposed by Norrefeldt *et al.* [38], a good agreement was achieved between the simulation results and experiments, as shown in Figure 2.6.

Figure 2.6. Zoning of room with ceiling inlet and outlet [38].

It is observed from recent applications that the zonal model is mainly used in describing the air with feeble momentum forces due to its incapability of solving momentum conservation equation. Therefore, some studies which are well performed using the CFD may not be available using the zonal model.

2.1.1.6 Computational fluid dynamics (CFD) model

The CFD method has become an efficient tool for engineers and researchers to visualize and analyze fluid fields since early 1970s. Based on the conservation laws, CFD is rich in physical significance and describes the imperfectly mixed fields very well. The parameters solved, including the air temperature, velocity, and turbulence characteristics, are critically important to achieving thermal comfort. Many pieces of

CFD software are available, such as CFX, FLUENT, STAR-CD, and PHOENICS-CFD.

All of CFD models, no matter in what form, are based on the conservation equations of continuity, momentum, and energy. A representative momentum equation for unsteady, compressible, viscous flow in x -direction is written as

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u^2 + p - \tau_{xx})}{\partial x} + \frac{\partial(\rho uv - \tau_{yx})}{\partial y} + \rho f_x = 0 \quad (2.4)$$

where ρ is the density of gas, p pressure, f_x the volume heat in x -direction, τ_{xx} normal stress, τ_{yx} shear stress, u and v are the velocities in x - and y -directions respectively. The application fields of CFD are very plentiful and not limited to building simulation. In this section, the fields relevant to the present work are reviewed mainly in the CFD validation and improvement of CFD efficiency.

Due to the large amount of computational cost, most, if not all, of the present CFD models adopt approximations to predict the air velocity and temperature distributions. The approximations inevitably bring some uncertainties or errors to the results. Therefore, it is necessary for researchers and engineers to improve CFD models with higher accuracy, reliability, and speed, although CFD has been employed to visualize the thermal performance in buildings for over 30 years [16]. Hajdukiewicz *et al.* [39] proposed a formal calibration technique for the CFD models in natural ventilation systems, the method aimed at describing how to verify and validate CFD models qualitatively and quantitatively and was validated by the experimental data in a normally operating building, the flowchart of proposed methodology is shown in Figure 2.7. Zhai *et al.* [40] analyzed the most dominant turbulence models for CFD prediction of air distributions in indoor environment, it is concluded that the universally preferable

turbulence model for all patterns of indoor-airflow does not exist, that is, one model performs well for one case but often poorly in another. Several studies [41-44] obtained good agreements between the results of the proposed CFD models and experiments.

Figure 2.7. Formal calibration algorithm of CFD model in indoor environment [39].

In addition to the model validation, some researchers made great efforts on improving the efficiency of numerical schemes. Pirker and Lichtenegger [45] developed a fast recurrence CFD model for the simulation of passive scalar transport in pseudo-periodic flow, whereas, the proposed model had several limitations, namely the process periodicity, transport passiveness, and data storage requirement. James Lo *et al.* [46] presented a method coupling CFD with tunnel testing to evaluate the performance of wind-induced ventilation, first, the wind tunnel pressure was measured in a small-scale building model, the measured data was then inputted as boundary conditions of the proposed CFD model for the test house, the results showed a good agreement with the full scale experimental data. Wang and Wong [47] proposed a coupling strategy between building simulation (BS) and CFD for natural ventilation, and the result showed that the proposed strategy effectively improved the accuracy and efficiency of the ventilation performance prediction for naturally ventilated system. Jiang *et al.* [48] introduced a new algorithm fusing sensor observations with a given CFD solution for

airflow field estimation, the simulation result of 2D case showed that the estimated airflow field via their strategy is better than that calculated from the traditional Gappy POD method.

Concluded from recent works of literature, it is popular to make efforts on improving the accuracy and reducing the computational cost for CFD model, such as coupling CFD with other tools and correcting CFD data by on-site sensor observation. It is noted that most efforts are given on the improvement of airflow field estimation in steady state and few on that of transient state. Therefore, the improvement of efficiency of the transient CFD algorithm is necessary and valuable for better visualization of indoor environment in a dynamic manner.

2.1.2 Thermal modelling of earth-sheltered building

2.1.2.1 Mathematical models

Figure 2.8. Heat transfer model for earth-sheltered buildings.

A typical heat transfer model [49] for earth-sheltered buildings is illustrated in Figure 2.8, the overall heat balance equation is defined as below [49, 50],

$$G_{H(V)} = SR_{H(V)} + R_{skyH(V)} - R_{surH(V)} + CE_{H(V)} - LE_{H(V)} \quad (2.5)$$

where, the subscripts H and V indicate the horizontal and vertical soil surfaces, G is the total energy absorption, SR the absorbed shortwave sun radiation energy, R_{sky} the longwave sky radiation energy, R_{sur} the longwave radiation energy of soil surface, CE the energy due to convection, LE the energy due to the latent evaporation, and LR_{H-V} the longwave radiation between horizontal and vertical surfaces.

In order to analyze the effect of building envelopes on the thermal performance of the earth-sheltered building, Luyang Shi *et al.* [51] conducted dynamic energy simulation using the platform of DeST, which calculated the heat across the ground-coupled envelopes fast and accurately by the frequency response analysis (FRA) technique [52]. Alberto Barbaresi *et al.* [53] [54] developed a method for underground cellar to assess the reliability of the simulation result from EnergyPlus by comparing it with experimental data, and indicated that EnergyPlus was capable of heat calculation in underground scenarios with appropriate assumptions. In a study conducted by Morteza Hazbei *et al.* [55], the CFD simulation results were verified by experimental measurements for an underground shelter called “shavadoon” as shown in Figure 2.9 and it was demonstrated that the energy conservation and thermal comfort could be achieved through the passive heating and cooling systems of earth-sheltered buildings. To determine the effects on the energy demand of earth-sheltered building by soil thermal properties, M. Staniec and H. Nowak [49] calculated the surface temperature of different soils using FlexPDE and then applied them as boundary conditions to the energy balance calculations in EnergyPlus.

Figure 2.9. Diagram of Shavadoon.

Based on the above literature survey, the majority of previous research focused on the thermal and energy performance of underground buildings with constant temperature of surrounding soils, and there were very few investigations on the temperature variation of soils affected by the air-conditioning of underground buildings and on the potential energy saving due to the varying soil temperature.

2.1.2.2 Influential parameters

It is well known that the soil may be utilized as a thermal mass for interior temperature modulation [56], leading to lower soil temperature than the ambient temperature in summer and higher in winter [57]. In order to fully realize the energy saving potential of earth-sheltered buildings, it becomes essential to disclose the key influential parameters on thermal and energy performance of earth-sheltered buildings.

Based on the physical and thermal properties of the soil, Kusuda [58] and Labs [59] derived a numerical model for computation of undisturbed soil temperature at any time and depth, which was validated by experimental measurements at various locations [60], the equation is shown below,

$$T(z, t) = T_{mean} - T_{amp} e^{-z\sqrt{\pi/365\alpha}} \times \cos\left(\frac{2\pi}{365}(t - t_0 - \frac{z}{2}\sqrt{365/\pi\alpha})\right) \quad (2.6)$$

where $T(z, t)$ is the temperature of undisturbed soil at depth z (m) and time t (day), T_{mean} the average ambient temperature, T_{amp} the amplitude of ambient temperature, α the soil

thermal diffusivity (m^2/day), and t_0 the day with the lowest ambient temperature. Al-Temeemi [61] adopted Equation (2.6) for earth temperature calculations and compared the heat transfer through a wall contacted with the soil at various depths, it is found that heat flow through the subsurface wall reduced with increasing soil depth. Staniec [49] examined the heating and cooling loads of earth-sheltered buildings in different types of soils and concluded that both the thermal diffusivity coefficient of soil and the contacting area between the building envelope and soil had significant influence on the energy use of earth-sheltered buildings. A research by Rees [62] investigated the heat transfer through ground floor slabs with different ground moisture content beneath buildings, and the results showed a reduction in the total heat flux to the ground with increasing groundwater table depth. Yuan [63] compared the thermal performance of underground buildings with various building envelope materials and demonstrated that the thermal conductivity of the building materials played a critical role in the heat transfer of the envelope. Zhao [64] stated that the ventilation system of underground building was essential for the human comfort and health and designed a mechanically ventilated system for a huge underground facility, the simulation results showed that the proposed ventilation system was efficiently workable for removing both the heat and air pollution in the underground facility.

In all the studies reviewed here, it is concluded that the parameters, namely the depth below the ground surface, soil properties such as thermal properties and humidity, building envelope materials, and ventilation system, have significant influence on the thermal and energy performance of earth-sheltered or underground buildings.

2.2 Control strategies of indoor environment and earth-sheltered building

2.2.1 Control strategies of indoor environment

With the significant increase of energy demand and growing focus on the quality of life in buildings including thermal comfort, visual comfort, and IEQ, optimization strategies for HVAC system are capturing increasing attention from researchers and engineers. Therefore, the development of efficient control methods in HVAC system is particularly important with its prominent effects on the building thermal comfort and energy conservation. Usually, various control methods for HVAC system are classified as classical control, hard control, soft control, hybrid control, and other control techniques [10].

2.2.1.1 Classic control

Due to its easy implementation and low cost, the classical control, consisting of on/off and proportional (P), proportional-integral (PI), and proportional-integral-derivative (PID) control, has played a crucial role in building automation and is still widely used in existing buildings.

The on/off controller has only two positions, either it is fully closed or fully open, namely the controller does not operate at any intermediate position. Kang *et al.* [65] developed a novel on/off control technique using fuzzy logic to maintain human comfort in buildings, on/off controller was adopted due to its structural simplicity, and fuzzy method was used to overcome its limitations. Chinnakani *et al.* [66] compared various control schemes, including a traditional on/off control, an intelligent on/off controller, and an optimal controller, in regulating temperature and humidity in facilities, the results implied the optimal controller was the best-suited choice to regulate thermal comfort.

As a control loop feedback mechanism, the PID controller calculates and minimizes the difference between the measured data and set point of the process variable. Wemhoff [67] presented a calibration method by applying successive optimization on the set of PID coefficients for reducing the energy consumption of the system, the results showed that the energy reduction reached up to 29% using this method. In the research of Zhang *et al.* [68], a PID controller optimized by MPC is employed to control the temperature control of an industrial surfactant reactor, the overall strategy made use of the simplicity and good control performance respectively from PID and MPC. Salazar and Méndez [69] developed a closed-loop thermal comfort control system for a trans-critical CO₂ refrigeration cycling, the linear governing equations and the PID control were adopted to define the best control scenarios.

In recent years, the classical control method has contributed only a bit to the literature of control application on HVAC system. The on/off controller is incapable of the control for moving process with time delays. Tuning of the PID parameters is always cumbersome, and the performance would degrade if the tuning conditions deviate from the operating conditions [10].

2.2.1.2 Hard control

Generally, the hard control methods are classified as gain scheduling control (GSC), nonlinear control, robust control, optimal control, and model predictive control (MPC).

For the GSC, piecewise linear regions are divided from a nonlinear system, then a linear PI or PID controller is designed and assigned to each of the linear regions with a different set of coefficients. Krzaczek and Kowalczyk [70] applied the proposed GSC system on the system of indirect passive heating and cooling of building to achieve a constant temperature, the result showed a good agreement with the experimental data.

The control law for nonlinear controller design, such as adaptive control technique, is to derive the nonlinear system with a stable state while achieving the control objectives. In the research of Hongli *et al.* [71], multi-variable nonlinear adaptive control algorithms of humidity and temperature were developed for energy-efficient control in HVAC system. Beghi and Cecchinato [72] designed an adaptive controller for tandem scroll compressor and packaged air-cooled water chiller, the proposed controller was verified to cut down the system energy cost and to show outstanding regulation performance in process applications.

The robust control aims at achieving good control performance while disturbances are time-varying and parameters are changing. In the research of Cheng *et al.* [73], a robust control was presented for the air-handling unit of variable air volume (VAV), two independent modules, including the reset control of supply air temperature and static pressure, were designed as different from traditional control. The proposed control system was validated to be effective in energy saving and thermal comfort.

The purpose of the optimal control is to improve indoor environmental condition with minimal energy consumption by solving an optimization problem. Examples showed the optimal control strategy was applied on passive building thermal storage with real-time pricing [74], borehole thermal energy storage systems [75], HVAC system with imperfect predictions [76], *etc.*

From above review, it is shown that the implementation of hard controller is comprehensive and well established. However, specifications of additional parameters are required by many of these methodologies, which are difficult and impractical to integrate them into HVAC system. Among these hard control methods, MPC is one of the most promising approaches, since it is available to integrate constraint handling,

disturbance rejection, real-time control of slow movement, and energy saving approaches into the controller construction [10].

2.2.1.3 Soft control

Soft control methodologies mainly include fuzzy logic (FL) control and ANN control which are comparatively new methods applied on digital controllers.

Based on the fuzzy logic, the FL control system utilizes logical variables that take on continuous values ranging from 0 to 1 for the analysis of analog inputs. Attia *et al.* [77] developed an FL control for the air-conditioning system to achieve low energy-cost and thermal comfort, which showed a higher energy efficiency than PID control. Hussain *et al.* [78] improved the fuzzy controllers' performance, namely the indices of predicted mean vote (PMV) and predicted percentage dissatisfied (PPD), in HVAC system using approaches of computational intelligence and optimization.

Inspired by biological neural networks, ANNs refer to a family of models used to estimate or approximate functions depending on a large number of inputs. As one of black box modelling methods, the formulation of ANN control is not necessarily involved with fundamental knowledge of the process. In order to evaluate the thermal comfort and energy consumption of the decoupled bi-linear HVAC system with VAV and variable water flow, Jahedi and Ardehali [79] proposed a wavelet-based artificial neural network (WNN) for self-tuning of a PD controller to control the temperature and relative humidity of a zone, and the efficiency of the proposed algorithm was higher than that of classical PD controller. Mustafaraj [80] proposed a linear parametric autoregressive model with external inputs (ARX) and a neural network-based nonlinear autoregressive model with external inputs (NNARX) for predicting the thermal

performance in an open office and they were proved to be useful for air quality improvement.

Concluded from above, in order to apply the techniques of FL control and ANN control on HVAC system, the comprehensive knowledge of the system operation and massive training data under various operating conditions are required, which may not be practical and acceptable for many systems.

2.2.1.4 Hybrid control

As implied, hybrid controllers are formulated by combining different types of models and control methods, such as the fusion of soft and hard control strategies. Examples of typical hybrid control are introduced below.

In the research of Wei *et al.* [81], a hybrid fuzzy-PID controller that runs fuzzy and PID controller simultaneously was applied to the VAV system for various factors affected by VAV terminal control. Fuzzy control was implemented to solve the nonlinear uncertainty in the case of deviating from the operating point, and PID control was applied to the work area to control the characteristics of high precision. The proposed controller was verified to obtain the expected control effect in the VAV air conditioning test platform.

Ng *et al.* [82] proposed a model predictive controller for an air-conditioning system with a variable-speed drive air compressor, the internal model was an artificial neural network which was trained online. By comparing the result of the presented control algorithm with those of a PID controller and a model predictive controller with an offline trained ANN model, it showed that the proposed control algorithm performed better on set point tracking and noise tolerance, since it was capable of learning the real time behavior of automotive air conditioning in various operation conditions.

The hybrid control method is popular due to its capability in taking advantages of coupled control algorithms. However, it also inherits the shortcoming of those techniques, such as a large number of data required for training from soft control.

2.2.1.5 Model development for model predictive control (MPC) system

Generally, the internal models in MPC are adopted to predict ventilation performance, energy consumption, and system output, with respect to the change of control inputs. The models integrated into MPC controllers are mainly classified as physics-based models, black-box models, and grey-box models, depending on the knowledge employed to derive the models [9].

A physical model is firstly developed by the description of a system or process of interest and then specified by the prior knowledge of the system or process. Mainly, Physics-based models are based on fundamental physics, such as the conservation laws of continuity, momentum, and energy. These detailed or simplified equations derived usually perform well on prediction under allowed operating conditions, due to the effectiveness and validation of the elementary assumptions and laws used in the modelling within the required range. Atthajariyakul and Leephakpreeda [83] developed a model to analyze the air quality, human comfort, and energy use in HVAC system with the physical knowledge of air temperature and velocity, humidity, and CO₂ concentration, the proposed methodology was validated by experimental data to be applied well to HVAC system in the dynamic determination of indoor air parameters. In the study of Wu and Sun [84], thermodynamic equations were utilized to determine the model structure and order for computing indoor air temperature in office buildings, and the model's effectiveness on both short- and long-term periods was validated by extensive measurements over 109 days. Xu *et al.* [85] presented a computer model for

a rooftop unit with a new designed evaporative water cooler using the equations of either heat and mass transfer or fluid flow, and the proposed model was calibrated with experimental results.

The black-box model, also known as data-driven model, is constructed based on the empirical system behaviors with no requirement of the understanding on the process, and the parameters involved have no physical meaning. Generally, the typical algorithms for the black-box model development are polynomial curve fits and ANNs. Castilla *et al.* [86] proposed two models, namely the ANN and polynomial expansions, for the PMV index within MPC frameworks in HVAC system, the accuracy and advantage of the proposed models were tested by experiments. In the study of Afram and Janabi-Sharifi [87], black-box models of the residential HVAC system were developed based on several identification techniques, transfer function, ANN, process, state-space, and autoregressive exogenous, ranks of the models were evaluated considering their relative performance. Identified from numerous CFD simulation data, Zerihun Desta *et al.* [88] proposed a reduced-order model to control the dynamics of an imperfectly mixed fluid field in a room.

The main advantage of grey-box model based control lies on the combination of physics-based and black-box models, that is, the complexities of the model structures and the computational costs are reduced by parameter estimation from training data, while the parameters still include certain physical significance [9]. In the research of Afram and Janabi-Sharifi [89], grey-box models were developed to provide the cost estimation and evaluate the performance for a residential HVAC, the identification technique was utilized to estimate the parameters of the subsystem models with data measured from the instrumented TRCA-ASH HVAC systems. Fayazbakhsh [90]

proposed a grey-box model to identify the on/off set points effectively in HVAC system, on the basis of governing equations and system heat balance, and the exponential temperature correlations were determined by measured data. An experimental study was conducted to show that the influenced energy cost by the determination of set points can reach up to 49% for the same desired temperature.

From the above review, it is found that CFD is not directly integrated into the model development of MPC system. It would be a promising way to couple CFD with MPC system, which takes advantages of both techniques, namely the CFD's performance on predicting accurately internal dynamics of imperfectly mixed fluid fields and MPC's tolerance with time delays and external disturbances for system, only if the CFD model is simplified with an acceptable computational cost.

2.2.2 Control strategies of earth-sheltered building

Figure 2.10. Schematic for control system of underground stations [91].

In order to achieve energy saving and thermal comfort in historic underground built environment, Stazi [92] proposed a smart indoor climate control system based on the balance of hygrothermal loads and indicated the possibility to be extended to other building heritage types. Vaccarini [91] developed an MPC for underground stations, as shown in Figure 2.10, based on a Bayesian environmental prediction model and applied

it to a metro station in Barcelona, while the results showed more than 30% of energy reduction were achieved in the ventilation system with acceptable thermal comfort level. A predictive model was presented by Lee [93] to remove the effects of outdoor air quality on indoor air quality in underground space, and the results showed the proposed model reduced the prediction error of PM concentration and energy demand by 20% and 64% respectively. Based on the literature survey, few studies have paid attention to the development and experimental setup of optimal control system for the earth-sheltered building by considering the variation of soil temperature.

2.3 Remarks

This chapter reviews the studies on the thermal modelling and control strategies of indoor environment and earth-sheltered building. According to the results of literature survey, several possible contributions arising from the present thesis are proposed below.

- So far no study has been conducted on the direct coupling of CFD model with control system, due to the CFD high nonlinearity and enormous computational cost. It is promising to perform the CFD coupled with control strategy, if the disadvantages of CFD model are overcome.
- The heat flux transferred from soil to earth-sheltered building has not been studied if the heat storage capacity of soil is considered. It is necessary to develop an efficient CFD model for the prediction of the transferred heat flux, as well as to couple the CFD model with energy simulation (ES) for the accurate energy calculation of earth-sheltered buildings.

- Few studies have paid attention to the control system design of earth-sheltered buildings. It is thus significant to develop an optimal strategy for the thermal control and energy efficiency of earth-sheltered buildings, by considering the time-varying temperature of surrounding soil.

Chapter 3

Development of Novel Strategy of Simplified Computational Fluid Dynamics Based Model Predictive Control (SCFD*b*MPC) for Real-time Optimization of Thermal Performance in Indoor Environment

This chapter presents the development of a novel strategy called SCFD*b*MPC for the real-time optimization of thermal performance in indoor environment. Section 3.1.1 introduces the detailed procedures for the operation of SCFD*b*MPC. As specified in Section 3.1.2, a CFD model is simplified based on the governing equations and several assumptions. Subsequently, a numerical algorithm, namely the pressure-implicit with splitting operators (PISO), is utilized to solve the proposed incompressible flow problem. Section 3.1.3 depicts the development of SCFD*b*MPC system by integrating the simplified CFD model into the MPC system. Section 3.2 elaborated the verification of the developed SCFD*b*MPC system with its full CFD counterpart. Finally, case studies are conducted in Section 3.3 to evaluate the performance of SCFD*b*MPC system.

3.1 Methodology

3.1.1 Strategy description

Computational Fluid Dynamics (CFD) is an efficient tool to assist researchers in analyzing HVAC system quickly, precisely, and economically [94]. Based on the conservation laws of mass, momentum, and energy, CFD describes well the internal dynamics of heat and mass transfer in imperfectly mixed fluids [95]. The performance

of MPC mainly depends on the internal model integrated to predict the future states of the system. Therefore, combination of the CFD model with real-time control system becomes a promising and innovative way to save energy and achieve thermal comfort in indoor environment, as long as the CFD model is simplified desirably, since the high complexity of CFD model hinders its integration into the real-time control system.

In the present work, the Simplified CFD based MPC (SCFD*b*MPC) strategy is developed by integrating a simplified CFD model into the MPC system. As shown in Figure 3.1 for the SCFD*b*MPC flowchart, based on the boundary and initial conditions, the thermodynamic parameters of fluid field are predicted first using simplified CFD model. By minimizing the errors between these estimated thermal distributions and set point values, the control inputs are then computed via the optimal algorithm, subjected to the constraints and cost function. Subsequently, the control inputs are imposed to the CFD model as boundary conditions for the prediction of fluid field in next time step. By this way, the current computational step ends, and the new loop starts with the latest control inputs obtained from the last step.

Figure 3.1. Flowchart for SCFD*b*MPC.

3.1.2 Development of simplified CFD model

Several assumptions are made in the present CFD model to reduce the complexity of the problem, as shown below.

- Ideal, viscous, and unsteady flow is assumed.
- Normal stress is negligible compared with shear stress.
- Volume force and volume heat are negligible.
- The compressibility of air is negligible, due to low air speed.
- Constant viscosity coefficient and thermal conductivity are assumed, due to low temperature variation.

In order to simplify the CFD model, the three-dimensional air-conditioned room is modeled in a two-dimensional domain with limited grids, and a simple example is shown in Figure 3.2.

Figure 3.2. Simplified air-conditioned room.

In the simplified CFD model, boundary conditions are imposed along walls. The parameters of inlet airflow are considered as control inputs, such as temperature and air velocity. The velocity of the occupancy could be treated as a no-slip condition or a value much smaller than the surrounding velocity. By CFD simulation, temperature and

air velocity are computed at grid points, such as (1, 1), (2, 2), and (2, 1) in this simple example.

3.1.2.1 Simplification of governing equations

CFD model is built upon classical conservation laws of physics and may provide accurate results. Governing equations for fluid flow include the conservations of continuity, momentum, and energy, as shown below [95].

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} = 0 \quad (3.1)$$

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u^2 + p - \tau_{xx})}{\partial x} + \frac{\partial(\rho uv - \tau_{yx})}{\partial y} + \rho f_x = 0 \quad (3.2)$$

$$\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho v^2 + p - \tau_{yy})}{\partial y} + \frac{\partial(\rho uv - \tau_{xy})}{\partial x} + \rho f_y = 0 \quad (3.3)$$

$$\frac{\partial(E_t)}{\partial t} + \frac{\partial[(E_t + p)u + q_x - u\tau_{xx} - v\tau_{xy}]}{\partial x} + \frac{\partial[(E_t + p)v + q_y - v\tau_{yy} - u\tau_{yx}]}{\partial y} - \rho \dot{q} - \rho \mathbf{f} \cdot \mathbf{V} = 0 \quad (3.4)$$

Equation (3.1) is for mass conservation law, Equations (3.2) and (3.3) are for momentum conservation law in x - and y -directions, Equation (3.4) is for energy conservation law, where ρ is the gas density, p pressure, E_t total energy, $\mathbf{f}$ volume force vector, $\mathbf{V}$ velocity vector. u and v are the velocities in x - and y -directions respectively, f_x and f_y the volume heat in x - and y -directions respectively, τ_{xx} and τ_{yy} normal stress, τ_{xy} and τ_{yx} shear stress, q_x and q_y the heat flux in x - and y -directions.

The number of equations is less than that of unknown parameters, and additional equations are given as

$$p = \rho RT \quad (3.5)$$

$$\tau_{xy} = \tau_{yx} = \mu \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \quad (3.6)$$

$$\tau_{xx} = \lambda (\nabla \cdot \mathbf{V}) + 2\mu \frac{\partial u}{\partial x} \quad (3.7)$$

$$\tau_{yy} = \lambda(\nabla \cdot \mathbf{V}) + 2\mu \frac{\partial v}{\partial y} \quad (3.8)$$

$$q_x = -k \frac{\partial T}{\partial x} \quad (3.9)$$

$$q_y = -k \frac{\partial T}{\partial y} \quad (3.10)$$

$$E_t = \rho \cdot (c_v T + \frac{u^2 + v^2}{2}) \quad (3.11)$$

where T is temperature, R specific gas constant, μ molecular viscosity coefficient, λ second viscosity coefficient, k thermal conductivity, c_v specific heat at constant volume.

As well known, the full Navier-Stokes equations are highly nonlinear, and thus they are unavailable to be integrated directly into the control loop. In order to reduce the modelling complexity mathematically and computationally, the assumptions below are adopted for the simplified CFD model.

- $f_x = 0, f_y = 0$.
- $\mathbf{f} \cdot \mathbf{V}, \dot{q} = 0$.
- $\tau_{xx} = \tau_{yy} = 0$.
- ρ, μ and k are constants.

The governing equations are simplified as the proposed CFD model, as given below.

Mass conservation

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (3.12)$$

Momentum conservation

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + \frac{1}{\rho} \frac{\partial p}{\partial x} - \frac{\mu}{\rho} \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) = 0 \quad (3.13)$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + \frac{1}{\rho} \frac{\partial p}{\partial y} - \frac{\mu}{\rho} \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) = 0 \quad (3.14)$$

Energy conservation

$$\frac{\partial T}{\partial t} = -u \frac{\partial T}{\partial x} - v \frac{\partial T}{\partial y} + \frac{k}{\rho c_v} \frac{\partial^2 T}{\partial x^2} + \frac{k}{\rho c_v} \frac{\partial^2 T}{\partial y^2} + \frac{\mu}{\rho c_v} \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right)^2 + 2 \frac{\mu}{\rho c_v} \left(\frac{\partial u}{\partial x} \right)^2 + 2 \frac{\mu}{\rho c_v} \left(\frac{\partial v}{\partial y} \right)^2 \quad (3.15)$$

3.1.2.2 Numerical algorithm for incompressible flow

As well known, it is always difficult to obtain analytical solutions for general partial differential equations, especially it is impossible for Navier-Stokes equations, although an analytical solution provides a perfect closed-form expression for the dependent variable all over the computational domain. In contrast, most of the popular approaches to solutions for partial differential equations are numerical techniques such as finite difference or finite element methods, although they provide approximate solutions only at discrete grid points in the domain. In the present work, the finite difference method is used for simulation of indoor velocity and temperature distributions in a dynamic manner. The pressure correction technique [96], which is widely applied in the numerical solution of the incompressible flow, is adopted here for pressure modification to satisfy the mass conservation law in every step. The technique is embodied in many algorithms, such as the semi-implicit method for pressure-linked equations (SIMPLE), SIMPLE Revised (SIMPLER), and pressure-implicit with splitting operators (PISO). The PISO algorithm is adopted in the present work since it is highly efficient for solving the problem of transient flow with no iterations involved.

Staggered grids

Figure 3.3. Staggered grids for PISO algorithm [97].

The staggered grid comprises two types of nodes, namely the solid grid and open grid points, as illustrated in Figure 3.3. The temperatures and pressures are computed at the solid grid points labeled (I, J) , and the velocities u and v are computed at the open grid points labeled (i, J) and (I, j) , respectively.

Procedures of pressure-implicit with splitting operators (PISO)

PISO algorithm is a pressure-velocity calculation procedure for Navier-Stokes equations especially for unsteady incompressible flow without iterations and with large time steps [98]. PISO is designed to satisfy mass conservation with one predictive step and two corrector steps. By assuming n as the last time step, * the prediction of the current time step, ** the first calibration of the current time step, *** the second calibration of the current time step, the detailed procedures are given below.

Predictive step

In the predictive step, the momentum equations are solved explicitly and are shown below [95]

$$u_{i,j}^* = u_{i,j}^n + A^n \Delta t - \frac{\Delta t}{\rho \cdot \Delta x} \cdot (p_{I+1,j}^n - p_{I,j}^n) \quad (3.16)$$

$$v_{I,j}^* = v_{I,j}^n + B^n \Delta t - \frac{\Delta t}{\rho \cdot \Delta y} \cdot (p_{I,j+1}^n - p_{I,j}^n) \quad (3.17)$$

where

$$A = -\left[\frac{(u^2)_{i+1,j}^n - (u^2)_{i-1,j}^n}{2\Delta x} + \frac{u_{i,j+1}^n \cdot (v_{I,j}^n + v_{I+1,j}^n) - u_{i,j-1}^n \cdot (v_{I,j-1}^n + v_{I+1,j-1}^n)}{4\Delta y} \right] \quad (3.18)$$

$$+ \frac{\mu}{\rho \cdot \Delta^2 x} \cdot (u_{i+1,j}^n + u_{i-1,j}^n - 2u_{i,j}^n) + \frac{\mu}{\rho \cdot \Delta^2 y} \cdot (u_{i,j+1}^n + u_{i,j-1}^n - 2u_{i,j}^n)$$

$$B = -\left[\frac{(v^2)_{I,j+1}^n - (v^2)_{I,j-1}^n}{2\Delta y} + \frac{v_{I+1,j}^n \cdot (u_{i,j}^n + u_{i,j+1}^n) - v_{I-1,j}^n \cdot (u_{i-1,j}^n + u_{i-1,j+1}^n)}{4\Delta x} \right] \quad (3.19)$$

$$+ \frac{\mu}{\rho \cdot \Delta^2 y} \cdot (v_{I,j+1}^n + v_{I,j-1}^n - 2v_{I,j}^n) + \frac{\mu}{\rho \cdot \Delta^2 x} \cdot (v_{I+1,j}^n + v_{I-1,j}^n - 2v_{I,j}^n)$$

1st calibration step

In the first calibration step, corresponding to the pressure field p^* , a new velocity field, including u^{**} and v^{**} , is given by

$$u_{i,j}^{**} = u_{i,j}^n + A^n \Delta t - \frac{\Delta t}{\rho \cdot \Delta x} \cdot (p_{I+1,j}^* - p_{I,j}^*) \quad (3.20)$$

$$v_{I,j}^{**} = v_{I,j}^n + B^n \Delta t - \frac{\Delta t}{\rho \cdot \Delta y} \cdot (p_{I,j+1}^* - p_{I,j}^*) \quad (3.21)$$

Substituting Equations (3.18) and (3.19) into Equations (3.20) and (3.21) respectively, the equations become

$$u_{i,j}^{**} = u_{i,j}^* - \frac{\Delta t}{\rho \cdot \Delta x} \cdot (p'_{I+1,j} - p'_{I,j}) \quad (3.22)$$

$$v_{I,j}^{**} = v_{I,j}^* - \frac{\Delta t}{\rho \cdot \Delta y} \cdot (p'_{I,j+1} - p'_{I,j}) \quad (3.23)$$

where $p' = p^* - p^n$. Substituting Equations (3.22) and (3.23) into the continuity equation, the pressure correction formula is derived as

$$ap'_{i,j} + bp'_{i+1,j} + bp'_{i-1,j} + cp'_{i,j+1} + cp'_{i,j-1} + d = 0 \quad (3.24)$$

where

$$a = 2 \left[\frac{\Delta t}{(\Delta x)^2} + \frac{\Delta t}{(\Delta y)^2} \right] \quad (3.25)$$

$$b = -\frac{\Delta t}{(\Delta x)^2} \quad (3.26)$$

$$c = -\frac{\Delta t}{(\Delta y)^2} \quad (3.27)$$

$$d = \frac{\rho}{\Delta x} (u_{i,j}^* - u_{i-1,j}^*) + \frac{\rho}{\Delta y} (v_{i,j}^* - v_{i,j-1}^*) \quad (3.28)$$

Equation (3.24) is solved using a numerical relaxation technique. Substituting the obtained result into Equations (3.22) and (3.23), u^{**} and v^{**} are then achieved.

2nd calibration step

The equations of the second calibration step for velocities are written as

$$u_{i,j}^{***} = u_{i,j}^n + A^* \Delta t - \frac{\Delta t}{\rho \cdot \Delta x} \cdot (p_{i+1,j}^{**} - p_{i,j}^{**}) \quad (3.29)$$

$$v_{i,j}^{***} = v_{i,j}^n + B^* \Delta t - \frac{\Delta t}{\rho \cdot \Delta y} \cdot (p_{i,j+1}^{**} - p_{i,j}^{**}) \quad (3.30)$$

Substituting Equations (3.20) and (3.21) into Equations (3.29) and (3.30) respectively, the equations become

$$u_{i,j}^{***} = u_{i,j}^{**} + (A^* - A^n) \Delta t - \frac{\Delta t}{\rho \cdot \Delta x} \cdot (p_{i+1,j}'' - p_{i,j}'') \quad (3.31)$$

$$v_{i,j}^{***} = v_{i,j}^{**} + (B^* - B^n) \Delta t - \frac{\Delta t}{\rho \cdot \Delta y} \cdot (p_{i,j+1}'' - p_{i,j}'') \quad (3.32)$$

where $p'' = p^{**} - p^*$.

Assuming

$$u_{i,j}^{**\wedge} = u_{i,j}^{**} + (A^* - A^n) \Delta t \quad (3.33)$$

$$v_{i,j}^{**\wedge} = v_{i,j}^{**} + (B^* - B^n)\Delta t \quad (3.34)$$

Equations (3.31) and (3.32) are then written as

$$u_{i,j}^{***} = u_{i,j}^{**\wedge} - \frac{\Delta t}{\rho \cdot \Delta x} \cdot (p_{i+1,j}'' - p_{i,j}'') \quad (3.35)$$

$$v_{i,j}^{***} = v_{i,j}^{**\wedge} - \frac{\Delta t}{\rho \cdot \Delta y} \cdot (p_{i,j+1}'' - p_{i,j}'') \quad (3.36)$$

Substituting Equations (3.35) and (3.36) into continuity equation, the 2nd pressure correction formula is formed as

$$ap_{i,j}'' + bp_{i+1,j}'' + bp_{i-1,j}'' + cp_{i,j+1}'' + cp_{i,j-1}'' + d = 0 \quad (3.37)$$

where

$$a = 2 \left[\frac{\Delta t}{(\Delta x)^2} + \frac{\Delta t}{(\Delta y)^2} \right] \quad (3.38)$$

$$b = -\frac{\Delta t}{(\Delta x)^2} \quad (3.39)$$

$$c = -\frac{\Delta t}{(\Delta y)^2} \quad (3.40)$$

$$d = \frac{\rho}{\Delta x} (u_{i,j}^{**\wedge} - u_{i-1,j}^{**\wedge}) + \frac{\rho}{\Delta y} (v_{i,j}^{**\wedge} - v_{i,j-1}^{**\wedge}) \quad (3.41)$$

Substituting the results of corrected pressure field into Equations (3.35) and (3.36), the final corrected results as u^{***} and v^{***} are achieved [97].

3.1.2.3 Boundary conditions

The simplified CFD model adopts no-slip boundary condition. The implementation of such boundary conditions in staggered grids is much more complicated than that in collocated grids. For example, the nodes for velocity u do not exist on the horizontal wall, as illustrated in Figure 3.4. By introducing the fictitious point, boundary conditions for the velocities parallel to the walls are obtained using averaging, which gives

$$u_{wall} = \frac{1}{2} (u_{i,j=1} + u_{i,j=-1}) \quad (3.42)$$

Figure 3.4. Boundary conditions for the velocity u near a horizontal wall.

It is noted that $u_{i,J=-1}$ is the velocity located outside the physical wall (fictitious point).

u_{wall} is the velocity of the grid points on the wall, it equals to zero as prescribed in the no-slip boundary condition. Therefore, the boundary condition for the velocity u near a horizontal wall is given as

$$u_{i,J=-1} = -u_{i,J=1} \quad (3.43)$$

On the horizontal wall, the nodes for velocity v exist, and the no-slip condition $v_{wall} = 0$ is applied directly. On a vertical wall, where the nodes for velocity u exist and those for v do not, the similar conditions as above are applied.

It is also observed from Figure 3.5 that, the nodes for temperature and pressure do not exist on both horizontal and vertical walls. By introducing the fictitious points, the boundary conditions for pressure and temperature are written as

$$P_{I,J=1} = P_{I,J=-1} \quad (3.44)$$

$$\frac{T_{I,J=1} + T_{I,J=-1}}{2} = T_{wall} \quad (3.45)$$

Figure 3.5. Boundary conditions for temperature and pressure.

3.1.2.4 Source code development and verification of simplified CFD model

Source code development

CFD model is built upon classical conservation laws and provides good prediction of fluid field and thermal distribution. The governing equations of fluid flow include the conservations of continuity, momentum, and energy. In the present work, the finite difference method is used for simulation of the indoor temperature and velocity distributions in a dynamic manner, PISO algorithm is employed for the simplified CFD model to solve the incompressible unsteady flow problem. The procedures of PISO algorithm are detailed as follows.

1. Set up of the boundary and initial conditions.
2. Prediction of the intermediate velocity fields by solving the discretized momentum equations.
3. Calculation of new pressure field by solving the pressure equation with the assistance of mass conservation law.
4. Update of the velocity fields and the boundary conditions based on the new pressure field.

5. Calculation of the final velocity fields by repeating steps 3-4 twice.

Microsoft Visual Studio [99], as an integrated development environment from Microsoft, is utilized for coding of the simplified CFD simulation program. In the present work, the programming language of C++ is adopted for the source code development of the simplified CFD model. As a result, the parameters of the airflow, such as u , v , and T , are predicted from the CFD program with the input information, including the boundary conditions, initial conditions, and known occupancy. The processing interface is shown in Figure 3.6 for the CFD simulation program.

Figure 3.6. Interface of CFD simulation program.

Model verification

In order to verify the model, the transient temperatures predicted by the simplified model are compared with its full CFD counterpart using commercial software ANSYS/FLUENT, under the same boundary and initial conditions. The equilibrium state simulated by FLUENT, when the inlet x -velocity $u = 0.5$ m/s, inlet y -velocity $v = 0.5$ m/s, and inlet temperature $T = 27^\circ\text{C}$, is adopted as the initial fluid field for the simplified CFD model and FLUENT model. The boundary conditions for FLUENT and simplified CFD model are shown in Table 3.1.

Table 3.1. Boundary conditions for FLUENT and simplified CFD models.

Type	FLUENT	Simplified CFD model
------	--------	----------------------

Inlet	$u = 0.5 \text{ m/s}, v = 0.5 \text{ m/s}, T = 20 \text{ }^{\circ}\text{C}$	$u = 0.5 \text{ m/s}, v = 0.5 \text{ m/s}, T = 20 \text{ }^{\circ}\text{C}$
Outlet	Pressure Outlet	Pressure Outlet
Wall	No-slip boundary condition	No-slip boundary condition

The temperature of Grid points T₁ and T₂, as shown in Figure 3.7, is compared between the simplified CFD and FLUENT models at various time steps. In order to examine the computational accuracy of simplified CFD model quantitatively, the cumulative variation of root mean square error (CVRMSE) is introduced and is given by [100]

$$CVRMSE = \frac{\sqrt{\sum_{i=1}^{10} ((F_i - S_i)^2 / 10)}}{\sum_{i=1}^{10} F_i / 10} \quad (3.46)$$

where F_i and S_i are the simulated temperatures at time t_i via FLUENT and simplified CFD model, respectively.

Figure 3.7. (a) Grid points T₁ and T₂ studied in the mesh of simplified CFD model, and (b) comparison between simulation results of FLUENT and simplified CFD model.

From the results shown in Figure 3.7(b), the CVRMSEs in the simplified CFD model for T₁ and T₂ are computed as 4.67% and 4.45% respectively. A better computational accuracy may be achieved if the appropriate meshing sizes are taken in spatial and time domains for the simplified CFD model. However, the accuracy of simplified CFD

model is sufficient at this level to describe the thermal distribution with acceptable computational cost. As a result, it becomes available to integrate the proposed finite-difference CFD models into the real-time control loops, in order to achieve the thermal comfort and energy saving.

3.1.3 Development of novel strategy for SCFD δ MPC

As well known, MPC is widely used as one of the advanced control methodologies, due to the capability of handling input and output constraints. The performance of MPC is mainly based on the capability of the internal model to predict the future output of the system. Meanwhile, CFD model is distinguished as a desirable tool for predicting thermal environment in the HVAC system. Therefore, a novel strategy by coupling the CFD model with MPC technique is developed as a potential approach for optimal control of the HVAC system. It is noted that one of the challenges in the proposed algorithm is the high nonlinearity of the CFD model, although several assumptions are made to simplify the CFD equations. In order to overcome the problem due to high nonlinearity, the successive linearization technique is employed here to replace the nonlinear model [101], using a series of equations linearized around the current state variables. The formulation of the presently developed strategy is detailed below.

3.1.3.1 Formulations for MPC

Figure 3.8. Basic idea of MPC [14].

MPC utilizes an internal model for prediction of the system behaviour from the current time to a future prediction horizon, and computes the control inputs by the minimization of the cost function [14]. The basic idea of MPC is shown in Figure 3.8, where k is the current time step, H_p the prediction horizon, $y(t)$ the actual system output at time t , $s(t)$ the set point trajectory at time t , $r(t|k)$ the reference trajectory at time t which starts from the current output $y(k)$, $y(t|k)$ the predicted output at time t . A linearized, discrete-time, state-space model of the system is written as

$$x(k+1) = Ax(k) + Bu(k) \quad (3.47)$$

$$y(k) = C_y x(k) \quad (3.48)$$

$$z(k) = C_z x(k) \quad (3.49)$$

where x is an n -dimensional state vector, u is an l -dimensional input vector, y is an m_y -dimensional measured output vector, and z is an m_z -dimensional vector of output which is controlled to satisfy the set points.

The cost function V penalizes the error between the predicted output $\hat{z}(k+i|k)$ and the proposed reference trajectory $r(k+i|k)$, and is written as

$$V(k) = \sum_{i=H_w}^{H_p} \|\hat{z}(k+i|k) - r(k+i|k)\|_{Q(i)}^2 + \sum_{i=0}^{H_u-1} \|\Delta\hat{u}(k+i|k)\|_{R(i)}^2 \quad (3.50)$$

$$\Delta\hat{u}(k+i|k) = \hat{u}(k+i|k) - \hat{u}(k+i-1|k) \quad (3.51)$$

where $\hat{u}(k+i|k)$ is the predicted input, H_u is the control horizon, and $H_u < H_p$ is usually assumed. Generally, there are constraints imposed on the input as well as the controlled outputs. The constraints over the control and prediction horizons are written as

$$E \text{vec}(\Delta\hat{u}(k|k), \dots, \Delta\hat{u}(k+H_u-1|k), 1) \leq \text{vec}(a, b, \dots, c) \quad (3.52)$$

$$F \text{vec}(\hat{u}(k|k), \dots, \hat{u}(k+H_u-1|k), 1) \leq \text{vec}(a, b, \dots, c) \quad (3.53)$$

$$G \text{vec}(\hat{y}(k+H_w|k), \dots, \hat{y}(k+H_p|k), 1) \leq \text{vec}(a, b, \dots, c) \quad (3.54)$$

where E, F and G are matrices of suitable dimensions, $\text{vec}(a, b, \dots, c)$ denotes the vector $(a, b, \dots, c)^T$.

3.1.3.2 Successive linearization for SCFDbMPC

It is clear that the equations mentioned in Section 3.1.3.1 are based on a linear internal model of MPC system. However, many processes are nonlinear sufficiently to preclude the application of linear MPC system, such as the simplified CFD model. Therefore, growing attentions are drawn to develop the algorithms appropriate for nonlinear systems. Some techniques are proposed to deal with the high nonlinearity of the internal model involved with MPC system, such as the sequential model solution and

optimization, successive linearization, simultaneous model solution and optimization, and alternative nonlinear MPC formulations [102]. The successive linearization method is adopted in the present work, since it is well developed and widely employed.

The general time-varying nonlinear model is assumed in the following form

$$\dot{x}(t) = f(x(t), u(t)) \quad (3.55)$$

where x is the state vector, u the input signal. Assuming x_n and u_n as the nominal system trajectory and nominal system input respectively, and the motion of the nonlinear system is in the neighborhood of the nominal point, the equations for $x(t)$ and $u(t)$ are given as

$$x(t) = x_n(t) + \Delta x(t) \quad (3.56)$$

$$u(t) = u_n(t) + \Delta u(t) \quad (3.57)$$

where $\Delta x(t)$ and $\Delta u(t)$ denote small quantities. Substituting Equations (3.56) and (3.57) into Equation (3.55), it becomes

$$\dot{x}_n(t) + \Delta \dot{x}(t) = f(x_n(t) + \Delta x(t), u_n(t) + \Delta u(t)) \quad (3.58)$$

Expanding the right side into a Taylor series about the nominal point, it becomes

$$\dot{x}_n(t) + \Delta \dot{x}(t) = f(x_n, u_n) + \frac{\partial f}{\partial x}(x_n, u_n) \Delta x(t) + \frac{\partial f}{\partial u}(x_n, u_n) \Delta u(t) + o(\Delta x(t), \Delta u(t)) \quad (3.59)$$

By doing simplification and truncating the higher-order terms, the linear differential equation is given as

$$\dot{x}(t) = \frac{\partial f}{\partial x}(x_n, u_n) x(t) + \frac{\partial f}{\partial u}(x_n, u_n) u(t) \quad (3.60)$$

The form of this equation is transformed as the same as that of a linear model, and it is implemented in much the same way. However, it is noted that $\dot{x}$ is now a perturbation of the time derivative. Also different from the linear MPC system, the exact linearization about a nominal point of a system leads to a time-varying linear model, since the state x_n varies continuously with time.

3.2 Verifications with commercial software Fluent

The developed SCFD*b*MPC system is implemented in MATLAB environment. In order to validate the model, the output temperatures predicted by SCFD*b*MPC system are compared with corresponding FLUENT results, due to little related published work and experimental study. For this purpose, firstly the control inputs and output temperatures are achieved by the present SCFD*b*MPC system under time-varying set points. The control signals for intake air flowrate are then inputted into its counterpart of FLUENT as boundary conditions, and comparisons are made between the output temperatures of SCFD*b*MPC system and its counterpart of FLUENT in a dynamic manner.

For case studies of the SCFD*b*MPC system, a benchmark model is adopted as shown in Figure 3.9. The numbered grid points serve as the monitoring positions to be controlled by SCFD*b*MPC system to meet the set point values. The equilibrium state simulated by FLUENT, when the inlet x -velocity $u = 0.5$ m/s, inlet y -velocity $v = 0.5$ m/s, and inlet temperature $T = 30^\circ\text{C}$, is imposed as initial fluid field to the SCFD*b*MPC system.

Figure 3.9. Computational grids for SCFD*b*MPC system.

In this section, by assigning the time-varying set point values to the control system, some control simulations are performed by the SCFD*b*MPC system. In the present study, the temperatures at Grid points 3 and 9 are considered as the controlled outputs. The upper and lower limits of inlet temperature are subjected to the hard constraints of 17°C and 32°C, respectively. The time step $\Delta t = 1$ s is assumed and the set point value is changed at time $t = 11$ s from 24.5°C to 30°C.

The Model Predictive Control (MPC) Toolbox embedded in the software MATLAB is employed here to compute the control inputs at each time step. The results are shown in Figures 3.10 and 3.11 for Grid points 3 and 9, respectively. It is observed from Figures 3.10(a) and 3.11(a) that the output temperatures are controlled efficiently by the proposed SCFD*b*MPC system to approach the time-varying set points. Moreover, the output temperature of Grid point 3 approaches the set points faster than that of Grid point 9. Probably this is because the position of Grid point 3 is closer to the inlet and directly affected by the inlet temperature variation. As seen in Figures 3.10(b) and 3.11(b), the input temperatures rise immediately with the increase of the set point value. In addition, it is found that the inlet temperature for Grid point 3 is higher than that for Grid point 9, because Grid point 3 is located closer to the inlet and requires less cooling energy to reach the same set point. It is thus shown that the proposed SCFD*b*MPC system is sensitive to the variation of temperature set point.

(a) Output temperature.

(b) Input temperature.

Figure 3.10. Control simulation results at Grid point 3.

(a) Output temperature.

(b) Input temperature.

Figure 3.11. Control simulation results at Grid point 9.

In order to verify the SCFD δ MPC system, the output temperatures of Grid points 3 and 9 are compared with corresponding FLUENT simulation results, by applying the input temperatures shown in Figures 3.10(b) and 3.11(b) to the FLUENT model as inlet boundary conditions. The results are shown in Figure 3.12(a) and (b) for Grid points 3 and 9, respectively. Using Equation (3.46), the cumulative variation of root mean square error (CVRMSE) for the output temperatures at Grid points 3 and 9 are achieved as 2.5% and 4.6% respectively, indicating that good agreement is achieved between SCFD δ MPC and FLUENT results. Therefore, the SCFD δ MPC system is verified to be a workable platform for optimal control and dynamic prediction of thermal distributions of indoor environment and is capable of tracking the prescribed set point changes at various monitoring points in indoor environment.

It is noted that the research work will be more significant and conclusive, if the simulation result can compare with any experimental results. However, so far little related experimental study has been done. Moreover, the present work, coupling CFD directly with real-time MPC, is the first of its kind and is more focused on the

methodology and system development. The results obtained from FLUENT might not be the best but would be good enough to verify the present work at this level to describe the thermal distribution with an acceptable computational cost. The validation of the proposed system with experimental results will be taken as our next-step work.

(a) Grid point 3.

(b) Grid point 9.

Figure 3.12. Comparison between output temperature by SCFD δ MPC and FLUENT simulations with the same initial and boundary conditions.

3.3 Case studies of SCFDbMPC system for optimization of thermal performance in indoor environment

In this section, the impacts of key parameters, including the inlet and outlet locations, multiple outlets, and occupant movement, are studied on the performance of the SCFDbMPC system.

3.3.1 Effect of inlet and outlet locations

As well known, the pattern of airflow in a room has a considerable impact on ventilation efficiency evaluation. The fundamental physical factors for building designers to provide the most rational airflow pattern include the inlet and outlet locations. In this section, the effects of outlet and inlet locations on the performance of the proposed SCFDbMPC system are examined by case studies schematically shown in Figures 3.13 and 3.14, respectively. In terms of a control system, the west representative point (WRP) and east representative point (ERP) are selected as monitoring points, which are centrally located in the west and east of computational domain, respectively. The temperatures of WRP and ERP are controlled by the developed SCFDbMPC system as controlled outputs. The temperature of the inlet is considered as the control input. The initial temperature for the computational domain is assumed as 30°C. The upper and lower limits of inlet temperature are subjected to the hard constraints of 20°C and 32°C, respectively. The dynamically input temperature variation allowed is set to 2°C per 1 s. The time step of 1 s is adopted, and the set point changes are applied at time $t = 2$ s and $t = 12$ s.

(a) Case 1.

(b) Case 2.

(c) Case 3.

Figure 3.13. Schematics for the cases with various outlet locations.

(a) Case 1.

(b) Case 2.

Figure 3.14. Schematics for the cases with various inlet locations.

3.3.1.1 Variation of outlet locations

West representative point (WRP)

The MPC Toolbox embedded in the software MATLAB is utilized here to compute the control inputs. The output temperature of WRP and control inputs for all the three cases, as shown in Figure 3.13, are plotted in Figure 3.15(a) and (b), respectively. Figures 3.16 and 3.17 show the contours of temperature and velocity vectors for the three cases at time $t = 12$ s and 22 s. It is seen from Figure 3.15(a) that the output temperatures at WRP for all the three cases are handled well by the SCFD b MPC system to approach the set points, while the controlled output in Case 3 responds fastest to the inlet temperature variation, followed by Cases 2 and 1. Moreover, it is found in Figure 3.15(b) that the inlet temperature in Case 3 varies in a relatively small range, indicating that the least effort or energy is required in Case 3 to control the WRP temperature to the given set points. The possible reason is that WRP in Case 3 is located in the mainstream of air flow and directly influenced by the inlet temperature change, as shown in Figures 3.16(c) and 3.17(c).

(a) Output temperature.

(b) Input temperature.

Figure 3.15. Comparison between control simulation results at WRP with various outlet locations.

$t = 12 \text{ s}$

$t = 22 \text{ s}$

Figure 3.16. Temperature contours for (a) Case 1, (b) Case 2, and (c) Case 3 at time $t = 12$ s and 22 s.

Figure 3.17. Contours of velocity vectors for (a) Case 1, (b) Case 2, and (c) Case 3 at time $t = 12$ s and 22 s.

East representative point (ERP)

The output temperature of ERP and control inputs for all the three cases, as shown in Figure 3.13, are plotted in Figure 3.18(a) and (b), respectively. Figures 3.19 and 3.20 show the contours of temperature and velocity vectors for the three cases at time $t = 12$ s and 22 s. It is observed from Figure 3.18(a) that the output temperature in Case 1 is controlled to approach the set points relatively fast and close, while the output temperature in Case 3 deviates far from the set points. It is shown in Figure 3.18(b), the input signals in all the three cases are the same ranging from 20-32°C, which is the constraint for the input temperature, indicating that the present system performs poorly in the temperature control of ERP by locating the outlets in the positions shown in Cases 2 and 3. The possible reason is that the monitoring point, ERP, becomes away from the mainstream of the flow by changing the outlet location from Case 1 to Case 2, as shown in Figures 3.19(b) and 3.20(b). In Case 3, ERP is located at or near recirculation zone

and hardly affected by the input temperature variation, as observed in Figures 3.19(c) and 3.20(c).

(a) Output temperature.

(b) Input temperature.

Figure 3.18. Comparison between control simulation results at ERP with various outlet locations.

$t = 12 \text{ s}$

$t = 22 \text{ s}$

Figure 3.19. Temperature contours for (a) Case 1, (b) Case 2, and (c) Case 3 at time $t = 12$ s and 22 s.

Figure 3.20. Contours of velocity vectors for (a) Case 1, (b) Case 2, and (c) Case 3 at time $t = 12$ s and 22 s.

3.3.1.2 Variation of inlet locations

WRP

Using the developed SCFD δ MPC, The output temperature of WRP and control inputs for all the three cases, as shown in Figure 3.14, are presented in Figure 3.21(a) and (b), respectively. Figures 3.22 and 3.23 show the contours of temperature and velocity vectors for the three cases at time $t = 12$ s and 22 s. As observed in Figure 3.21(a), the output temperature in Case 3 responds fast to the inlet temperature variation but is not close to the set point $T_{sp} = 24^{\circ}\text{C}$. This is possible because WRP is located at the recirculation zone of flow, although it is near the inlet, as shown in Figures 3.22(b) and 3.23(b). When the set point is changed to $T_{sp} = 27^{\circ}\text{C}$, the output temperatures in all cases are controlled and maintained well. In addition, it is found in Figure 3.21(b) that the variation range of input temperature is relatively small in Case 2, followed by Cases

3 and 1. Therefore, the control of the temperature at WRP is the most efficient by locating the inlet in Case 2, compared with Cases 1 and 3.

(a) Output temperature.

(b) Input temperature.

Figure 3.21. Comparison between control simulation results at WRP with various inlet locations.

$t = 12 \text{ s}$

$t = 22 \text{ s}$

Figure 3.23. Contours of velocity vectors for (a) Case 1, (b) Case 2, and (c) Case 3 at time $t = 12$ s and 22 s.

ERP

For the monitoring point, ERP, the output and input temperatures of the three cases, as shown in Figure 3.14, are shown in Figure 3.24(a) and (b), respectively. Figures 3.25 and 3.26 show the contours of temperature and velocity vectors for the three cases at time $t = 12$ s and 22 s. It is seen in Figure 3.24(a) that the output temperatures in both

Cases 1 and 3 are handled well to reach the set points, while that in Case 2 deviates from the set points. It is possible because ERP becomes far away from the mainstream of the air flow by locating the inlet in Case 2, as shown in Figures 3.25(b) and 3.26(b). Meanwhile, compared with Cases 1 and 2, the input temperature of Case 3 varies in a relatively small range of 22-32°C, as presented in Figure 3.24(b). This fact reveals that, among all the cases, the SCFD b MPC system performs the most efficiently in Case 3 under the same set point. The possible reason is that the monitoring point, ERP, is covered by the mainstream of flow in Case 3 as shown in Figures 3.25(c) and 3.26(c), and hence its temperature is controlled efficiently by adjusting the inlet temperature.

(a) Output temperature.

(b) Input temperature.

Figure 3.24. Comparison between control simulation results at ERP with various inlet locations

Figure 3.25. Temperature contours for (a) Case 1, (b) Case 2, and (c) Case 3 at time $t = 12$ s and 22 s.

Figure 3.26. Contours of velocity vectors for (a) Case 1, (b) Case 2, and (c) Case 3 at time $t = 12$ s and 22 s.

Based on the case studies, the developed SCFD**b**MPC system works well and efficiently for the optimal control of the indoor environment with different inlet and outlet locations. Moreover, it is implied that the control performance in the indoor environment is significantly affected by the locations of the inlet and outlet, and thus a better arrangement of the inlet and outlet locations has great potential to achieve a better thermal comfort with a lower cost for the control system.

3.3.2 Effect of multiple outlets

Using the temperature as the only control input is usually not efficient for the optimal control of a complicated system, such as a room with multiple outlets. In order to analyze the effect of multiple outlets on the performance of the SCFD**b**MPC system, two manipulated variables, including the velocities in x - and y -directions of the inlet, are adopted in the control system. The temperatures at the monitoring points, WRP and ERP, are taken as the controlled outputs. The initial temperature for the computational domain is assumed as 30°C. The inlet temperature is assumed constant and equals to 22°C. The velocities in x - and y -directions of the inlet are subjected to the constraints $-1(m/s) \leq v_x \leq 1(m/s)$ and $0(m/s) \leq v_y \leq 1(m/s)$ respectively. The allowable

dynamic changes of input velocities in both x - and y -directions are set to 0.2 m/s per 1 s. The time step $\Delta t = 1$ s and the temperature set point $T_{sp} = 24^\circ\text{C}$ are adopted for the control system. The analyzed four case studies are shown in Figure 3.27 schematically.

Figure 3.27. Schematics of the cases with multiple outlets.

WRP

The MPC Toolbox embedded in the software MATLAB is utilized here to compute the control inputs. The output temperature at WRP and control input of the four cases, as shown in Figure 3.27, are illustrated in Figures 3.28 and 3.29, respectively. Figure 3.30 shows the contours of temperature and velocity vectors of the four cases at the end of control. It is seen from Figure 3.28 that the temperatures at WRP are controlled well to the set point $T_{sp} = 24^\circ\text{C}$ for all the four cases. The reason may be that the inlet velocities

in x -direction are all negative values in the four cases as shown in Figure 3.29(a), indicating that the intake air is controlled to blow towards the monitoring point, WRP. A similar situation is observed in Figure 3.30 that the monitoring point, WRP, is covered by the mainstream of flow in all the four cases. Moreover, it is found in Figure 3.29(a) and (b) that the absolute values of the inlet velocities in x - and y -direction are largest in Case 1, followed by Case 3, Case 4, and Case 2, meaning that the temperature control of WRP is the most efficient in Case 2. This is possible because the outlets in Case 2 are located near WRP and the mainstream of flow is controlled to cover WRP efficiently.

Figure 3.28. Output temperature at WRP for the cases with multiple outlets.

(a) Inlet velocity in x -direction.

(b) Inlet velocity in y-direction.

Figure 3.29. Control inputs at WRP for the cases with multiple outlets.

Figure 3.30. Contours of temperature and velocity vectors for (a) Case 1, (b) Case 2, (c) Case 3, and (d) Case 4 at time $t = 10$ s.

ERP

The output temperatures at ERP are shown in Figure 3.31 for the four cases shown in Figure 3.27. As observed from the figure, the output temperatures are controlled well by the present SCFD δ MPC system to the set point in all the four cases. The inlet velocities in x - and y -directions of the four cases are compared in Figure 3.32(a) and (b), respectively. As illustrated in Figure 3.32(a), the inlet velocities in x -direction increase first and are all positive values in the four cases, indicating that the intake air is controlled to blow towards ERP. In addition, it is demonstrated in Figure 3.32(b) that the inlet velocity in y -direction keeps constant at its upper limit for the first 5 seconds and then decreases as the temperature of ERP becomes lower than the set point $T_{sp} = 24^{\circ}\text{C}$. Moreover, it is shown from Figure 3.32 that the total magnitude of the inlet velocity in Case 2 is largest among the four cases, because all the outlets in Case 2 are located far from ERP and it requires more effort for the control system to adapt the

mainstream of flow to cover ERP. The contours of temperature and velocity vectors for the four cases at the end of control are shown in Figure 3.33, where the monitoring point, ERP, is covered by the mainstream of flow in all the four cases. It is thus concluded that the proposed SCFD δ MPC system works efficiently for the optimal control of the indoor environment with multiple outlets.

Figure 3.31. Output temperature at ERP for the cases with multiple outlets.

(a) Inlet velocity in x -direction.

(a) Inlet velocity in y-direction.

Figure 3.32. Control inputs at ERP for the cases with multiple outlets.

Figure 3.33. Contours of temperature and velocity vectors for (a) Case 1, (b) Case 2, (c) Case 3, and (d) Case 4 at time $t = 10$ s.

3.3.3 Effect of occupant movement

Occupant movement is one of the major factors influencing the building energy consumption and thermal comfort. It is crucial and promising for the control system to adjust the inlet air flowrate and direction based on the occupant movement. In the present study, the velocities in x - and y -directions of the inlet are considered as the control inputs, and the inlet temperature is assumed constant and equals to 22°C . Meanwhile, the temperature of the hot spot, which is caused by the intensive occupancy, is taken as the output. The initial temperatures for the hot spot and other computational grids are assumed as 35°C and 30°C , respectively. The velocities in x - and y -directions of the inlet are subjected to the constraints $-1(\text{m/s}) \leq v_x \leq 1(\text{m/s})$ and $0(\text{m/s}) \leq v_y \leq 1(\text{m/s})$ respectively. The allowable dynamic variations of input velocities in both x - and y -directions are set to 0.2 m/s per 1 s . The time step $\Delta t = 1 \text{ s}$ is

assumed for the control system. In this section, case studies by considering different movement patterns, different inlet and outlet locations, and multiple outlets are conducted to investigate the performance of SCFD b MPC system on the thermal control of indoor environment with occupant movement.

3.3.3.1 Different movement patterns

Figure 3.34. Schematics for the cases with various movement patterns of occupant.

The cases for different movement patterns are illustrated schematically in Figure 3.42, where the movement routes of the hot spot are 'a-b-c' and 'a-b-c-d-e' for Cases 1-3 and

Case 4 respectively and the movement of the hot spot occurs every 10 s. The velocities of the inlet as the control inputs are computed by the Model Predictive Control Toolbox embedded in the software MATLAB. The output temperature and control input are shown in Figure 3.35 for the four cases with different movement patterns of occupant. Figures 3.36 and 3.37 show the contours of temperature and velocity vectors for Cases 1-3 at time $t = 10$ s, 20 s, and 30 s and Case 4 at time $t = 10$ s, 20 s, 30 s, 40 s, and 50 s. It is observed in Figure 3.35(b, d, f, h) that, the output temperatures of the four cases are controlled well by the SCFD δ MPC system to the set point value of 24°C in all stages. This finding is verified by the fact that the moving hot spot is effectively covered by the mainstream of flow at the end of each stage, as shown in Figures 3.36 and 3.37. Moreover, it is illustrated in Figure 3.35(a, c, e, g) that the direction of inlet air flow is changed by mainly adjusting the velocity in x -direction corresponding to the hot spot movement, in order to control the mainstream of the air flow to cover the hot spot and hence cool down the hot spot efficiently. Taking the control input of Case 4 shown in Figure 3.35(g) as an example, in Stage (a) the velocity in y -direction decreases significantly from 1 m/s to 0.6 m/s during the time $t = 3$ s to $t = 5$ s and then keeps consistent, while the velocity in x -direction always equals to zero. This is probably because the hot spot in Stage (a) is located at the mainstream of the air flow and cooled down efficiently, when the inlet velocity in x -direction equals to zero. When the hot spot moves to the monitoring position (b), the inlet velocity in x -direction starts to increase and remains constant at 0.4 m/s from $t = 12$ s to $t = 19$ s, followed by a decrease to 0.2 m/s at $t = 20$ s. Meanwhile, the inlet velocity in y -direction remains constant at 0.8 m/s from $t = 11$ s to $t = 15$ s after a rise in the beginning, followed by a gradual decrease to 0.2 m/s from the time $t = 16$ s to $t = 20$ s. In Stage (c), both the velocities v_x and v_y increase at first and then decrease to 0.2 m/s and 0.4 m/s, respectively. In Stage

(d), as the monitoring position moves horizontally from (c) to (d), the velocity v_x drops significantly from 0.6 m/s to -1 m/s, and by then the monitoring position is covered by the mainstream changing from right-ward flow to left-ward flow. In the last stage (e), when the monitoring point returns to the origin, the velocity v_x turns to zero gradually which is the same to the beginning. It is thus concluded that the present SCFD b MPC system provides a satisfying tracking capacity of the occupant movement under the required set point. In next sections, more cases are studied by considering different inlet and outlet locations and multiple outlets, based on Case 4 as benchmark.

(a) Control input of Case 1.

(b) Output temperature of Case 1.

(c) Control input of Case 2.

(d) Output temperature of Case 2.

(e) Control input of Case 3.

(f) Output temperature of Case 3.

(g) Control input of Case 4.

(h) Output temperature of Case 4.

Figure 3.35. Control simulation results for the cases with various movement patterns of occupant.

Figure 3.36. Transient temperature contours for (a) Case 1, (b) Case 2, (c) Case 3, and (d) Case 4.

Figure 3.37. Contours of transient velocity vectors for (a) Case 1, (b) Case 2, (c) Case 3, and (d) Case 4.

3.3.3.2 Different inlet and outlet locations

Figure 3.38. Schematics of the cases with various inlet and outlet locations.

The schematics of Cases 1 and 2, which differ in the outlet and inlet locations respectively from the benchmark case, are shown in Figure 3.38. The control simulation results by SCFD*b*MPC system are plotted in Figure 3.39 for the two cases. Figures 3.40 and 3.41 show the contours of temperature and velocity vectors for the two cases at time $t = 10$ s, 20 s, 30 s, 40 s, and 50 s. It is observed from Figure 3.39(b) and (d) that the output temperature in Stage (c) is not controlled well to the set point $T_{sp} = 24^{\circ}\text{C}$ for both Cases 1 and 2. The possible reason is that, as observed in Figures 3.40 and 3.41, the mainstream of flow is controlled effectively to cover the hot spot in Stages (a, b, d, e) for the two cases, whereas the mainstream of flow may hardly reach the hot spot in Stage (c). Moreover, as shown in Figure 3.39(a), the absolute value of velocity v_x is relatively large in Case 1 compared with that in the benchmark case, in order to compensate the influence of moving the outlet to the right side of wall. In addition, it is seen from Figure 3.39(c) that the velocity v_y in Stage (d) is significantly higher than those in other stages. The possible reason is that the domain of interest in Stage (d) is easily covered by the recirculation zone of flow and a high velocity in y -direction is required to divert the mainstream of flow towards that domain, as shown in Figure 3.41(b).

(a) Control input of Case 1.

(b) Output temperature of Case 1.

(c) Control input of Case 2.

(d) Output temperature of Case 2.

Figure 3.39. Control simulation results for the cases with various inlet and outlet locations.

Figure 3.40. Transient temperature contours for (a) Case 1 and (b) Case 2.

Figure 3.41. Contours of transient velocity vectors for (a) Case 1 and (b) Case 2.

3.3.3.3 Multiple outlets

Figure 3.42. Schematics of the cases with multiple outlets.

The investigated four cases with multiple outlets are shown in Figure 3.42 schematically. The control simulation results by SCFD b MPC system are plotted in Figure 3.43 for the four cases. Figures 3.44 and 3.45 show the contours of temperature and velocity vectors for the four cases at time $t = 10$ s, 20 s, 30 s, 40 s, and 50 s. As observed in Figure 3.43, the output temperatures in all the stages are controlled well to 24°C for the four cases. However, it is noted in Figure 3.43(b) that the output temperature in Stage (d) decreases at first and then rebounds slightly from time $t = 33$ s to 35 s. The possible reason is that during that time period the domain of interest in Stage (d) is covered in the recirculation zone which is moving dynamically with the

change of inlet velocity. Moreover, the velocity v_x is found to follow a similar pattern in all the four cases. Specifically, the velocity v_x keeps constant and equals to zero in Stage (a) and then increases and maintains a positive value in Stages (b) and (c), followed by a decrease to a negative value in Stage (d), and finally turns to zero in Stage (e). Consequently, the inlet velocity direction is changed by adjusting v_x and v_y according to the position of occupant. This finding is verified by the fact that the moving hot spot is effectively covered by the mainstream of flow at the end of each stage, as shown in Figures 3.44 and 3.45. It is thus concluded that the present SCFD δ MPC system is very effective in tracking the occupant movement and maintaining thermal comfort by adjusting the inlet air flowrate and direction.

(a) Control input of Case 1.

(b) Output temperature of Case 1.

(c) Control input of Case 2.

(d) Output temperature of Case 2.

(e) Control input of Case 3.

(f) Output temperature of Case 3.

(g) Control input of Case 4.

(h) Output temperature of Case 4.

Figure 3.43. Control simulation results for the cases with multiple outlets.

Figure 3.44. Transient temperature contours for (a) Case 1, (b) Case 2, (c) Case 3, and (d) Case 4.

(d)

Figure 3.45. Contours of transient velocity vectors for (a) Case 1, (b) Case 2, (c) Case 3, and (d) Case 4.

3.4 Remarks

In this chapter, a novel system called SCFD*b*MPC is developed for the real-time optimization of thermal performance in indoor environment. Firstly, based on the two dimensional Navier-Stokes equations, a CFD model is simplified for the simulation of indoor environment, in order to significantly reduce computational cost with desired numerical accuracy. The simplified CFD model is then verified with its full CFD counterpart and integrated into the MPC algorithm to form SCFD*b*MPC system using successive linearization method. After the verification by FLUENT simulation results, the performance of the SCFD*b*MPC system is thoroughly examined by case studies. The results show that the SCFD*b*MPC system is an efficient workable platform for optimal control and dynamic prediction of thermal distributions in indoor environment, which adapts well to the time-varying set points, various boundary conditions, and occupant movement.

Apart from the active design strategy of simplified CFD based MPC as mentioned above, the earth-sheltered building, as one of passive cooling techniques, might also be beneficial to the sustainable development of buildings. Therefore, the next chapter presents the CFD modelling, CFD-coupled energy modelling, and full-CFD-coupled MPC design for earth-sheltered buildings, as well as case studies on their thermal, energy, and control performance.

Chapter 4

CFD and CFD-coupled Energy Modelling and Full-CFD-coupled Model Predictive Control (MPC) design for Earth-sheltered Building

In this chapter, the CFD and CFD-coupled energy modelling as well as full-CFD-coupled MPC design is presented for earth-sheltered building. As specified in Section 4.1, a transient two-dimensional (2D) CFD model is built up to analyze the heat flux transferred from soil to earth-sheltered building. Subsequently, the energy modelling for earth-sheltered building is introduced by coupling the developed CFD model with energy simulation. In addition, a predictive model to represent the dynamic thermal behavior of the earth-sheltered building is developed properly. According to the present predictive model and CFD simulation, a novel co-simulation strategy called full-CFD-coupled MPC is proposed for the thermal control of earth-sheltered building, which adapts well to the time-varying soil temperature. Furthermore, the CFD model is validated by published works, as presented in Section 4.2. Finally, the thermal, energy, and control performance is thoroughly examined for the earth-sheltered building through case studies, as elaborated in Section 4.3.

4.1 Methodology

4.1.1 CFD modelling

In order to characterize the time-varying heat flux across the envelope of earth-sheltered building, a CFD model is formed based on transient-state conservation equations of mass, momentum, and energy. In particular, the geometry, governing equations,

boundary conditions are presented in this section, followed by the mesh generation and grid independence analysis.

4.1.1.1 Geometry model

The analyzed problem for earth-sheltered buildings is illustrated schematically in Figure 4.1(a). The model mainly includes three parts, namely the undisturbed soil, disturbed soil, and earth-sheltered building. The undisturbed soil refers to the soil far away from the earth-sheltered building and hence is not influenced by the cooling effect of air-conditioning in the earth-sheltered building. The temperature of undisturbed soil mainly depends on the depth, soil thermal properties, and climatic conditions. Moreover, the disturbed soil represents the soil whose temperature is varied significantly with the cooling effect of the air-conditioning in earth-sheltered buildings. Enclosed by the soil, the earth-sheltered building is equipped with a scheduled air-conditioning system. The geometry and dimensions of the present 2D CFD model are shown in Figure 4.1(b). The 2D CFD geometry may not give accurate results as a 3D model but is necessarily adopted in the present work due to transient and long-term (up to one year) simulation.

Figure 4.1. Schematics for (a) 3-D physical model of the problem, (b) 2-D geometry and dimensions, and (c) computational domain and boundary conditions.

Regarding the computational domain, as shown in Figure 4.1(c), the surrounding soil is assigned to a thickness of 2 m, such that the domain is large enough to capture its temperature variation due to the cooling effect of air-conditioning. For the earth-sheltered building, a symmetrical construction is adopted with one inlet and one outlet. Moreover, the influence of internal heat gain and heat flux across the building envelope is incorporated into the thermal calculation of the air domain.

4.1.1.2 Governing equations

In the present CFD model, the heat transfer in the solid regions occurs primarily through conduction, while heat convection dominates in the air domain of earth-sheltered

building. Therefore, the fundamental heat transfer process for the earth-sheltered building is considered mainly in two parts, namely the heat convection between air domain and inner surface of building envelope and heat conduction in solid regions including wall, surrounding soil, and undisturbed soil. The model assumes that gas is ideal and flow is viscous, unsteady, and turbulent. Governing equations of fluid flow include the conservations of mass, momentum, and energy. On this basis, the conservation equations for the 2-D unsteady turbulent flow are given in the following forms [103].

Conservation of mass

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \mathbf{u}) = 0 \quad (4.1)$$

Conservation of momentum in the x-direction

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho uu)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} = -\frac{\partial p}{\partial x} + (\mu + \mu_t) \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) - \frac{2}{3} \rho \frac{\partial k}{\partial x} \quad (4.2)$$

Conservation of momentum in the y-direction

$$\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho vu)}{\partial x} + \frac{\partial(\rho vv)}{\partial y} = -\frac{\partial p}{\partial y} + (\mu + \mu_t) \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) - \frac{2}{3} \rho \frac{\partial k}{\partial y} \quad (4.3)$$

Conservation of energy

$$\frac{\partial \left[\rho \left(e + \frac{\mathbf{u}^2}{2} \right) \right]}{\partial t} + \frac{\partial(\rho u T)}{\partial x} + \frac{\partial(\rho v T)}{\partial y} = \left(\frac{\mu}{\text{Pr}} + \frac{\mu_t}{\sigma_t} \right) \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \quad (4.4)$$

where ρ is the gas density, t time, $\mathbf{u}$ velocity vector, p pressure, u the velocity in x -direction, v the velocity in y -direction. The shear stress transport $k - \omega$ (SST $k - \omega$) equation [104] is adopted here to model the turbulence, because it has higher accuracy and reliability among turbulent models and behaves appropriately in both the near-wall

and far-field zones [105]. The transport equations for the SST $k - \omega$ model [105] are described by

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + \tilde{G}_k - Y_k + S_k \quad (4.5)$$

$$\frac{\partial(\rho \omega)}{\partial t} + \frac{\partial(\rho \omega u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\omega} \right) \frac{\partial \omega}{\partial x_j} \right] + G_\omega - Y_\omega + D_\omega + S_\omega \quad (4.6)$$

where k is the turbulent kinetic energy, ω specific dissipation rate, μ_t the turbulent viscosity given by $\mu_t = \rho \frac{k}{\omega}$, $\tilde{G}_k$ is the generation of turbulent kinetic energy due to mean velocity gradients, G_ω is the ω generation, μ is the molecular viscosity coefficient, Y_k and Y_ω represent the dissipations of k and ω due to turbulence, Y_k and Y_ω are user-defined source terms, and D_ω represents the cross-diffusion term. The convective heat flux q between the air domain and wall is computed as [106]

$$q = h_f (T_w - T_f) \quad (4.7)$$

where h_f is the heat transfer coefficient, T_w the wall surface temperature, and T_f the air temperature. For the heat transfer in solid regions, the energy transfer equation is defined as [105]

$$\frac{\partial}{\partial t}(\rho h) = \nabla \cdot (k \nabla T) + S_h \quad (4.8)$$

where h is sensible enthalpy, k conductivity, T temperature, and S_h volumetric heat source. All the values of model constants refer to the FLUENT theory guide [105].

4.1.1.3 Boundary conditions

Regarding the boundary conditions, ‘no-slip wall’ condition is imposed to all the walls of the earth-sheltered building. The ‘mass flow rate’ and ‘pressure outlet’ are imposed to the boundaries of the inlet and outlet, respectively. Moreover, in order to make the

model close to the actual situation, a scheduled air-conditioning system is modelled using User Defined Functions (UDF), which is a toolbox embedded in ANSYS/FLUENT. The mass flow rate of the inlet is then controlled according to the schedule. A scheduled internal heat load is also modelled using the UDF as a heat source term in the air domain. The schedule is divided into two parts, namely the occupied and unoccupied hours. For the 24 hours of each day, the first 10 hours are termed the occupied hours during which the air-conditioning and internal heat load are activated, while the rest 14 hours are termed the unoccupied hours with the air-conditioning and internal heat load inactivated. The heat source in the proposed model is given based on the condition of a standard office, while the mass flow rate of the inlet air is determined by the energy balance formula [107] as shown below

$$\dot{Q}_{12} + \dot{Q}_{in} = \dot{m} \cdot (h_1 - h_2) = \dot{m} \cdot c_p (T_1 - T_2) \quad (4.9)$$

where $\dot{Q}_{12}$ is the heat transfer through the boundary, $\dot{Q}_{in}$ is the internal heat source, $\dot{m}$ is the mass flow rate of inlet air, c_p is the specific heat, $(h_1 - h_2)$ and $(T_1 - T_2)$ are respectively the enthalpy and temperature differences between the inlet air and zone air.

4.1.1.4 Mesh generation and grid independence analysis

In the present thesis, CFD modelling is conducted with the FLUENT code. According to Chen *et al.* [108], refining the grid size is an essential way for verification of CFD simulation results. Therefore, grid independence analysis is necessarily carried out to ensure that the obtained results are independent on the grid density. Two CFD models with the computational grid of 19,673 and 44,729 are investigated at the operating condition. The details for the case studies are shown in Table 4.1. The temperatures of Grid points (10, 7.5) and (17, 7.5) at various time steps are solved for comparison, as

shown in Figure 4.2. It is observed that the difference is negligible in the results of the two analyzed models. Therefore, the mesh model with 19,673 cells is selected to achieve a reasonable result with less computational cost, as shown in Figure 4.3.

Table 4.1. Case studies for the grid independence analysis.

Case	1-1	1-2	2-1	2-2
Coordinate	(10, 7.5)	(10, 7.5)	(17, 7.5)	(17, 7.5)
Cell number	19,673	44,729	19,673	44,729

Figure 4.2. Temperature comparison between two mesh models at different coordinates.

Figure 4.3. Computational grid for the CFD model of earth-sheltered building.

4.1.2 CFD-coupled energy modelling

In this section, a strategy coupling energy simulation (ES) with CFD is proposed for prediction of the energy demand of earth-sheltered buildings. The computer program

EnergyPlus and the CFD model developed in Section 4.1.1 are adopted here for the energy and CFD simulations, respectively. Compared with the conventional ES, the present ES coupled with CFD is able to provide results of higher accuracy for the earth-sheltered building, due to the complementary information of time-varying soil temperature profile provided by CFD. On the basis of the classical conservation laws, CFD describes the energy balance between the air domain and surrounding soils well. Meanwhile, EnergyPlus computes the heating and cooling loads necessarily to maintain thermal control set points, based on the equations of energy balance and heat and mass transfer. In order to achieve the annual energy demand of earth-sheltered buildings, firstly the varying temperature profile of surrounding soil with time is computed by CFD simulation, while the temperatures for the internal air in occupied and unoccupied hours are set constants and equal to 24°C and 27°C respectively. The achieved time-varying temperature profile of surrounding soil then becomes the boundary condition for the annual ES in EnergyPlus. The time steps of 30 seconds and 1 hour are adopted for CFD and energy simulations, respectively.

In the present study, a single-level earth-sheltered building with a length of 15 m, a width of 15 m, and a height of 3.3 m is assumed for the ES, which is consistent with the CFD model shown in Section 4.1.1. Because of the heavy loads for the earth-sheltered building, the reinforced concrete with a thickness of 0.3 m is adopted as the building structure.

For energy modelling of the earth-sheltered building, it is necessary to adopt the internal cooling loads properly, which consist of the occupancy load, lighting load, plug load, and air infiltration rate. In this thesis, the internal cooling loads for all cases are assumed

the same and are shown in Table 4.2. It is noted that the air infiltration equals to zero, as there is no air infiltration effect for earth-sheltered buildings.

Table 4.2. Internal cooling loads for ES [115].

Load types	Occupancy density, (people/m ²)	Occupancy activity, (W/people)	Lighting load, (W/m ²)	Plug load, (W/m ²)
Value	0.05	120	15	16.48

In order to simulate the most common situations, two types of schedules, namely the scheduled operation and full-day operation, are introduced in the present energy model. Regarding the scheduled operation, the schedules of lighting system, equipment, and occupancy are assumed in Figure 4.4(a)-(c), respectively. For the schedule of lighting system shown in Figure 4.4(a), the lighting is turned on starting from 8:00 am and turned off after 18:00 pm. For the schedule of equipment shown in Figure 4.4(b), the equipment is partially turned on, and the percentage in use remains 40% during the period from 18:00 pm to 8:00 am. It then increases and remains at 90% from 8:00 am to 18:00 as the daily peak load. As shown in Figure 4.4(c), there is no occupancy during the period from 18:00 pm to 8:00 am. Moreover, the peak load starts from 9:00 am to 17:00 pm except for the lunchtime from 12:00 pm to 1:00 pm. In terms of full-day operation, the fraction of lighting, equipment, and occupancy keep consistent through a whole day and equal to 0.9, 0.9, and 0.75, respectively. The scheduled operation is applicable for workplaces such as office and school, while the full-day operation is used to simulate scenarios operating on a 24-hour-a-day basis, like data centre, warehouse, and cold storage.

Figure 4.4. Schedules for (a) lighting system, (b) equipment, and (c) occupancy.

4.1.3 Full-CFD-coupled MPC strategy

By taking into account the effect of heat stored in surrounding soils, substantial energy saving might be achieved if optimal control is developed and applied to the HVAC system of earth-sheltered building. For this purpose, an optimal strategy, coupling full CFD simulation with MPC, is presented for earth-sheltered building in this section.

4.1.3.1 Strategy description

According to literature review detailed in Section 2.2.2, few published works were done on the development of control system for earth-sheltered buildings, due to the difficulty in modelling the temperature profile of surrounding soils subjected to the weather and scheduled air-conditioning system. In the present work, CFD simulation is innovatively

employed for the control strategy of earth-sheltered building, mapping both the temperature distribution of surrounding soil and heat flux across the envelope of the building. Generally, a much-simplified CFD model is necessary for its integration into real-time control, because a high time cost is required to achieve transient CFD results. In the modelling of earth-sheltered building however, the soil temperature responds slowly with time delays to both the climatic condition and cooling effect of air-conditioning, and thus the time cost might not become an issue. Therefore, it is feasible to couple a full CFD model with MPC for the thermal control and energy efficiency of earth-sheltered buildings.

Figure 4.5. Schematic of full-CFD-coupled MPC strategy for thermal control of earth-sheltered buildings.

In the present thesis, a novel co-simulation strategy between MPC and CFD is proposed for the temperature control of earth-sheltered building, as shown in Figure 4.5. The CFD model estimates the heat flux across the envelope of earth-sheltered buildings, based on the boundary and initial conditions. The heat flux with other disturbances is then inputted into the MPC system for the calculation of a sequence of future control inputs, by minimizing the gap between system outputs and set point values.

Furthermore, the mass flow rate of inlet air extracted from control inputs becomes a boundary condition in CFD simulation for prediction of the heat flux across the envelope of earth-sheltered building. The updated heat flux through the envelope is imposed to MPC system again to achieve the latest control inputs for the next loop.

4.1.3.2 MPC model

MPC structure

In addition to the basic structure of MPC [109], CFD code FLUENT is innovatively integrated into the temperature control strategy for the earth-sheltered building, as shown in Figure 4.6. With consideration of the boundary and initial conditions, the CFD model estimates the heat flux across the envelope of earth-sheltered buildings. The heat flux is then inputted into the process model to predict future outputs. By minimizing the errors between model outputs and set point values, a sequence of future control inputs is achieved using the optimal control system subjected to the cost function and constraints. Furthermore, the mass flow rate of inlet air becomes the boundary condition in CFD simulation for prediction of the updated heat flux across the envelope of earth-sheltered building. Together with the control inputs, the updated heat flux is introduced into the process model again to predict the outputs of next time steps.

Figure 4.6. Flowchart of full-CFD-coupled MPC algorithm for earth-sheltered buildings.

MPC formula

Model Predictive Control (MPC) represents an ample range of optimal algorithms that compute the control signal by prediction of a model of the process and the minimization of a cost function. MPC is proved a successful optimization approach by numerous researches and industrial applications. The success of MPC mainly attributes to (1) the intuitiveness, (2) the capability of multivariable control with constraints and disturbances, (3) the capability of handling nonlinear process, (4) the nature to compensate for measured disturbances as a feed-forward control, and (5) the compensation ability for dead times [109]. To implement the MPC strategy, a model is developed for prediction of future system outputs on the basis of past and current values. The predicted future behaviours and constraints are then taken account into the calculation of control inputs by minimizing the cost function. The typical state space model for MPC is described as below [110]:

$$x_{k+1} = Ax_k + Bu_k \quad (4.10)$$

$$y_k = Cx_k \quad (4.11)$$

where $x_k \in \mathbb{R}^{n_x}$ is the system state, $y_k \in \mathbb{R}^{n_y}$ is the system output, $u_k \in \mathbb{R}^{n_u}$ is the control input, k is the current time step, and A , B , and C are the matrices for the system, input, and output respectively. The quadratic cost function for MPC is described as follows [110]:

$$J(x_0, \{u_0, u_1, u_2 \dots\}) \doteq \sum_{k=0}^{\infty} (\|x_k\|_Q^2 + \|u_k\|_R^2) \quad (4.12)$$

where $\|v\|_S^2$ represents the form $v^T S v$ for any $v \in \mathbb{R}^{n_v}$ and $S = S^T \in \mathbb{R}^{n_v \times n_v}$, and Q , R are weighting matrices for particular states and inputs. The optimal value of the cost function is given by

$$J^*(x_k) \doteq \min_{u_k, u_{k+1}, u_{k+2}, \dots} J(x_k, \{u_k, u_{k+1}, u_{k+2} \dots\}) \quad (4.13)$$

which subject to the constraint formula

$$Fx + Gu \leq \mathbf{1} \quad (4.14)$$

where $F \in \mathbb{R}^{n_c \times n_x}$, $G \in \mathbb{R}^{n_c \times n_u}$, and $\mathbf{1}$ is a vector with elements equal to unity and the dimension is context dependent.

Model development

MPC uses an internal model to predict the system behavior, starting at the current time, over a future prediction horizon. Therefore, it is crucial to develop a model that represents the thermal behaviour of the earth-sheltered building properly in a dynamic manner. In order to develop the predictive model for the earth-sheltered building, several assumptions are necessarily adopted:

- The zone air is well mixed, namely the thermal distribution is uniform.
- No air infiltration, due to the closed environment for underground space.
- The mechanical work, friction, kinetic and potential energy are neglected, as they are small compared with the heat rate [107].

Figure 4.7. Heat gains and losses through earth-sheltered buildings.

Based on the first law of thermodynamics, the temporal energy change of the control volume equals to the sum of the total heat rate into the control volume and the enthalpy change of the control volume, as illustrated in Figure 4.7. The energy balance equations [107] for the proposed problem with above assumptions are described by

$$V_{za} \cdot \rho_{za} \cdot c_p \cdot \frac{dT_{za}}{dt} = \dot{Q}_{evl} + \dot{Q}_{in} + \dot{m} \cdot (h_{in} - h_{out}) \quad (4.15)$$

where,

$$h_{in} - h_{out} = c_p (T_{in} - T_{za}) \quad (4.16)$$

substituting Equation (4.16) into (4.15), the energy balance equation is written as

$$V_{za} \cdot \rho_{za} \cdot c_p \cdot \frac{dT_{za}}{dt} = \dot{Q}_{evl} + \dot{Q}_{in} + \dot{m} \cdot c_p \cdot (T_{in} - T_{za}) \quad (4.17)$$

where V_{za} , ρ_{za} , and T_{za} are the volume, density, and temperature of the zone air respectively, $\dot{Q}_{evl}$ is the heat rate transferred through the envelope, $\dot{Q}_{in}$ is the internal heat source, $\dot{m}$ is the mass flow rate of inlet air, c_p is the specific heat, $(h_{in} - h_{out})$ and $(T_{in} - T_{za})$ are respectively the enthalpy difference and temperature difference between the inlet air and zone air.

Though the thermal dynamic model for the earth-sheltered building is derived as shown in Equation (4.17), it is not able to be incorporated into the MPC system directly. Generally state space models are used to formulate the predictive control problem. For this purpose, Equation (4.17) is discretized using forward difference method as follows:

$$V_{za} \cdot \rho_{za} \cdot c_p \cdot \frac{T_{za}(k+1) - T_{za}(k)}{\Delta t} = \dot{Q}_{evl} + \dot{Q}_{in} + \dot{m} \cdot c_p \cdot (T_{in} - T_{za}) \quad (4.18)$$

By assuming the supply air temperature $T_{in} = 24^\circ C$, $\rho_{za} = 1.225 kg / m^3$, $c_p = 1006.43 j / kg \cdot K$, $V_{za} = 15m \times 15m \times 3.3m = 742.5m^3$, the energy balance equation is given as

$$T_{za}(k+1) = T_{za}(k) + \Delta t \cdot \left(-\frac{\dot{m}}{909.6} \cdot T_{za}(k) + \frac{287.15}{909.6} \cdot \dot{m} + 1.09e^{-6} \cdot \dot{Q}_{in} + 1.09e^{-6} \cdot \dot{Q}_{evl} \right) \quad (4.19)$$

In order to be integrated into the MPC system, Equation (4.19) is necessarily approximated to a state-space model, as described as follows:

$$x(k+1) = Ax(k) + Bu(k) + Cw(k) \quad (4.20)$$

$$y(k) = x(k) \quad (4.21)$$

where:

- $x(k) = T_{za}(k)$ is the state vector;
- $y(k) = T_{za}(t)$ is the output vector;
- $u(k) = \dot{m} \cdot \left(\frac{287.15 - T_{za}(t)}{909.6} \right)$ is the control input;
- $w(k) = \begin{bmatrix} \dot{Q}_{in} \\ \dot{Q}_{evl} \end{bmatrix}$ is the disturbance vector, while the internal heat gain, $\dot{Q}_{in}$, of

occupancy, lighting, and equipment is shown in Figure 4.8 for a typical day.

Figure 4.8. Internal heat gain schedule for earth-sheltered building in 24 hours.

The cost function V [14] penalizes the error between the predicted output $\hat{y}(k+i|k)$ and the proposed reference trajectory $r(k+i|k)$, and is written as

$$V(k) = \sum_{i=H_w}^{H_p} \left\| \hat{z}(k+i|k) - r(k+i|k) \right\|_{Q(i)}^2 + \sum_{i=0}^{H_u-1} \left\| \Delta \hat{u}(k+i|k) \right\|_{R(i)}^2 \quad (4.22)$$

$$\Delta \hat{u}(k+i|k) = \hat{u}(k+i|k) - \hat{u}(k+i-1|k) \quad (4.23)$$

where $\hat{u}(k+i|k)$ is the predicted input, H_u is the control horizon, and $H_u < H_p$ is usually assumed. Generally, there are constraints imposed on the input as well as the controlled outputs. The constraints over the control and prediction horizons are written as

$$E \text{vec}(\Delta\hat{u}(k|k), \dots, \Delta\hat{u}(k+H_u-1|k), 1) \leq \text{vec}(a, b, \dots, c) \quad (4.24)$$

$$F \text{vec}(\hat{u}(k|k), \dots, \hat{u}(k+H_u-1|k), 1) \leq \text{vec}(a, b, \dots, c) \quad (4.25)$$

$$G \text{vec}(\hat{y}(k+H_w|k), \dots, \hat{y}(k+H_p|k), 1) \leq \text{vec}(a, b, \dots, c) \quad (4.26)$$

where E, F and G are matrices of suitable dimensions, $\text{vec}(a, b, \dots, c)$ denotes the vector $(a, b, \dots, c)^T$.

4.2 Verifications with published results

In order to examine the present CFD model for the earth-sheltered building, comparisons are necessarily made with the results of other publications or experiments. Due to the fact that few publications are found on the heat exchange between the air of earth-sheltered building and surrounding soil, a similar study by Wu *et al.* [111] on earth-air heat exchanger which uses soil as a heat sink and air as the heat transfer medium is adopted here to verify the present CFD model. Simulation results are validated at depths $z = 1.6$ m, 3.2 m, and 5.0 m in July for the climatic condition of Guangzhou, China. The undisturbed soil temperatures $T_{us} = 26.37^\circ\text{C}$, 22.64°C , and 21.24°C for the investigated depths $z = 1.6$ m, 3.2 m, and 5.0 m, respectively. The ambient air temperature is shown in Figure 4.9, and the physical and thermal properties for air and soil are tabulated in Table 4.3.

Figure 4.9. Ambient air temperature for simulation.

Table 4.3. Physical and thermal properties for air and soil.

Material	Density, ρ (kg/m ³)	Specific heat, c (J/kg K)	Thermal conductivity, λ (W/m K)	Thermal diffusivity, α (m ² /s)
Soil	2050	1840	0.52	7.82×10^{-7}
Air	1	1000	0.026	1.56×10^{-7}

The results are shown in Figure 4.10 by comparing the outlet air temperature of the present CFD simulation with that of published study [111] in a dynamic manner. As illustrated in the figure, the trends are analogous for both models at various depths. Specifically, with time evolution, the outlet air temperature increases at first and reaches a peak at time $t = 14$ h, followed by a gradual decrease. Probably this is because the outlet air temperature follows closely to the variation of the ambient air temperature shown in Figure 4.9. Furthermore, it is found in Figure 4.10 that the outlet air temperature varies at a relatively low range when the buried depth is larger. The possible reason is that, with increasing depth, the soil temperature decreases and the air benefits better cooling effects from the surrounding soil. In addition, the cumulative variation of root mean square error (CVRMSE) for the output temperatures at depths $z = 1.6$ m, 3.2 m, and 5.0 m are achieved as 2.1%, 0.85%, and 2.7% respectively, indicating that good agreements are achieved. Therefore, the present CFD model is validated to be valid for further investigation.

Figure 4.10. Comparison of the present CFD simulation and published result for outlet air temperature [111].

4.3 Case studies of earth-sheltered building

4.3.1 Thermal performance by CFD simulation

In this section, the present CFD model is employed to study the effects of soil heat storage, buried depth, soil thermal property, and envelope material on the thermal performance of the earth-sheltered building subjected to the tropical climate in Singapore.

4.3.1.1 Effect of heat stored in soil

In order to analyse the effect of heat stored in soil, the thermal performance of earth-sheltered building in scheduled and full-day operations are predicted using the developed CFD model, as schematically shown in Figure 4.11. The buried depth $z = 14$ m is set, where the constant undisturbed soil temperature $T_{us} = 28.4^\circ\text{C}$.

Figure 4.11. Schematic of the cases in scheduled and full-day operations.

Case 1: Earth-sheltered building with scheduled air-conditioning

The predicted temperatures of the zone air, wall, and surrounding soil as functions of time t are shown in Figure 4.12. It is observed that, in each day, the zone air temperature decreases in occupied hours and falls to a bottom at the end of occupied hours, followed by a sharp increase when the air-conditioning is turned off, then it rises gradually in unoccupied hours and finally reaches a peak at the end. Moreover, the wall temperature decreases in occupied hours and then bounces back slightly in the unoccupied hours, while the surrounding soil temperature follows a similar trend but fluctuates in a much smaller range. Probably this is because the air-conditioning cools down the zone air, wall, and surrounding soil significantly in occupied hours. When the air-conditioning is turned off in the unoccupied hours, the wall and surrounding soil of the earth-sheltered building are heat up slightly by the far field soil with a constant temperature $T_{us} = 28.4^{\circ}\text{C}$. As a result, the zone air temperature also increases in unoccupied hours. It is also seen from Figure 4.12 that, the temperatures of the zone air, wall, and surrounding soil drop dramatically in first 10 days, followed by a gradual decrease from $t = 11$ days to $t = 40$ days. Finally, the temperatures of the zone air, wall, and surrounding soil are maintained to fluctuate in a relatively low range, compared with

the initial condition. The possible reason is that both the wall and surrounding soil are cooled down by absorbing and storing the cooling energy from the air domain of earth-sheltered building in occupied hours. In unoccupied hours when the cold air is not supplied, the surrounding soil temperature is expected to rise significantly with the heat transferred from undisturbed soil. However, the temperature variation of soil is largely delayed due to its high thermal inertia, and finally the earth-sheltered building reaches a dynamic heat balance with the soil.

Figure 4.12. Temperatures of the zone air, wall, and surrounding soil in the earth-sheltered building.

The typical velocity distribution and temperature contour of wall and surrounding soil are shown in Figure 4.13 at the time $t = 50$ days, when a dynamic heat balance is achieved between the earth-sheltered building and soil. It is observed from Figure 4.13 that, with time evolution, around a third part of the soil domain is cooled down to the average temperature of 27°C , compared with the initial temperature of 28.4°C . In order to demonstrate the horizontal and vertical temperature gradient of the surrounding soil, the temperatures of horizontally and vertically distributed points are monitored as

schematically shown in Figure 4.14(a), where the distance between every two adjacent monitoring points is equivalent as 0.36 m. The temperatures of the horizontal and vertical monitoring points as functions of time t are shown in Figure 4.14(b) and (c), respectively. It is seen from Figure 4.14(b) and (c) that the temperature gradient of the surrounding soil increases with time due to the cooling effect of the air-conditioning. Moreover, it is found that the closer the soil is to the earth-sheltered building, the greater the temperature gradient. This is possible because the undisturbed soil temperature maintains constant at the depth $z = 14$ m, while the temperature of the earth-sheltered building keeps decreasing due to the cooling effect of the scheduled air-conditioning. Consequently, the soil closer to the earth-sheltering building is cooled down more significantly.

(a) Velocity distribution of the air domain.

(b) Temperature contour of wall and surrounding soil.

Figure 4.13. Velocity and temperature distributions for the case of scheduled operation.

(a) Monitoring points.

(b) Temperature of horizontal monitoring points.

(c) Temperature of vertical monitoring points.

Figure 4.14. Schematic and temperature of monitoring points in surrounding soil.

Figure 4.15 illustrates the heat transferred across the envelope of earth-sheltered building as a function of time t . As shown in the figure, the heat transfer rate in occupied hours is much larger than that in unoccupied hours for each day. Probably this is because the heat transfer rate through the envelope mainly depends on the temperature difference of the wall and zone air. In unoccupied hours, the temperature difference almost falls to zero, as the zone air reaches a heat balance with the wall. In addition, it is obvious that, with time evolution, the average daily heat transfer rate through the envelope decreases with the decrease of the wall and surrounding soil temperatures, as shown in Figure 4.15. Meanwhile, the decrease of the heat transfer leads to a reduction in the cooling load for maintaining thermal comfort in the earth-sheltered building and consequently results in the potential energy saving for the earth-sheltered building if a control system is applied.

Figure 4.15. Heat transfer through the envelope of the earth-sheltered building.

Case 2: Earth-sheltered building with full-day air-conditioning

The temperatures of the zone air, wall, and surrounding soil, as well as the heat transfer rate through envelope, are predicted by the present CFD model, as shown in Figure 4.16, as functions of time t . It is observed from the figure that all temperatures and heat transfer rate decrease gradually at first and become consistent from $t = 16$ days. Compared with the results of scheduled operation in Figures 4.12 and 4.15, the temperatures and heat transfer rate in full-day operation decrease relatively fast, steep and smooth without daily fluctuation, as the air-conditioning system operates 24-hour-a-day.

Figure 4.16. Temperatures of the zone air, wall, and surrounding soil in the earth-sheltered building.

Figure 4.17 shows the temperature contour of the wall and surrounding soil when a heat balance is achieved in the case of full-day operation. Compared with the case of scheduled operation, the total cooled area of soil is significantly larger in the case of full-day operation. The temperature plots of the monitoring points as functions of time t are shown in Figure 4.18 for the investigated case. The temperatures of the monitoring points decrease in the first 15 days and then maintains constant. In addition, the temperature gradient increases with time and is shown to be greater for the soil closer to the building domain. Moreover, compared with the case of scheduled operation, the temperature distribution in this case is relatively uniform, indicating that more areas of the surrounding soil are influenced by the cooling effect of air-conditioning in full-day operation.

Figure 4.17. Temperature contour of wall and surrounding soil for the case of full-day operation.

(a) Temperature of horizontal monitoring points.

(b) Temperature of vertical monitoring points.

Figure 4.18. Temperature of monitoring points in surrounding soil.

In order to quantitatively evaluate and compare the energy saving potential of the earth-sheltered building under various boundary conditions, the index of overcooling coefficient, σ_{oc} , is proposed to describe the overcooled degree or energy saving potential for earth-sheltered buildings and is given by

$$\sigma_{oc} = \frac{\sum_{i=1}^N \frac{T_r - T_i}{T_r}}{N} \times 100\% \quad (4.27)$$

where T_i is the average temperature of the time step i during occupied hours, T_r is the reference temperature or zone temperature set point and is set to 298.15K (25°C) in this study, N is the total number of simulation time steps. The energy saving potential of the earth-sheltered building is positively correlated with the value σ_{oc} . Using Equation (4.27), the overcooling coefficients are computed as 0.31% and 0.48% for earth-sheltered building in scheduled and full-day operations, respectively.

4.3.1.2 Effect of soil thermal property

In order to investigate the influence of soil thermal property on the thermal performance of earth-sheltered buildings, four typical types of soils [112] differing in the thermal properties are investigated, as shown in Table 4.4. The thermal inertia, as a critical parameter in the soil, is defined as the degree of slowness with which the temperature of a body approaches that of its surroundings and is given by [113]

$$I = \sqrt{\rho c \lambda} \quad (4.28)$$

where ρ is the density, c is the specific heat, and λ is the thermal conductivity.

Figure 4.19. Schematic of the cases with soils of different thermal properties.

Table 4.4. Thermal properties for analyzed soils.

Type	Thermal conductivity (W/m K)	Volumetric heat capacity (J/m ³ K)	Thermal diffusivity (m ² /s)	Thermal inertia (J/m ² K s ^{1/2})
Soil 1	1.420	4.420×10 ⁶	3.210×10 ⁻⁷	2.506×10 ³
Soil 2	1.020	1.770×10 ⁶	5.800×10 ⁻⁷	1.343×10 ³
Soil 3	2.200	2.310×10 ⁶	9.600×10 ⁻⁷	2.254×10 ³
Soil 4	2.220	2.040×10 ⁶	1.080×10 ⁻⁶	2.128×10 ³

The investigated case studies are shown in Figure 4.19 schematically. Simulations of the thermal performance of the earth-sheltered buildings are conducted for the climate of Singapore. The depth for all case studies here is chosen as 14 m to clearly demonstrate the dependence of energy performance on thermal properties of soils, while the soil temperatures fluctuate at a small range and are assumed to be a constant value of 28.4°C, as shown in Figure 4.20.

Figure 4.20. Annual temperatures for analyzed soils at a depth of 14 m.

The simulation results are shown in Figure 4.21(a)-(d) for the average soil temperature, zone air temperature, wall temperature, and heat transfer rate through envelope in occupied hours, respectively. It is seen from Figure 4.21(a) that the surrounding soil temperatures for the analyzed soils drop sharply in the beginning and become consistent in the end. Moreover, by comparing the thermal properties of analyzed soils, it is found that the higher the thermal inertia I , the larger the magnitude of the decline. Similar trends are observed in Figure 4.21(b)-(d) for the zone temperature, wall temperature, and the heat transfer rate through the envelope, respectively. However, it is observed that the heat transfer rates through the envelope are nearly the same in Soil 1, Soil 3, and Soil 4. The probable reason comes from the fact that the heat transfer rate is linearly correlated to the temperature difference of the zone air and wall, which are equivalent for Soil 1, Soil 3, and Soil 4.

(a) Surrounding soil temperature.

(b) Zone air temperature.

(c) Wall temperature.

(d) Heat transfer rate through envelope.

Figure 4.21. Simulation results for the cases with soils of different thermal properties in occupied hours.

Temperature contours of the wall and surrounding soil are shown in Figure 4.22 for the analyzed cases after a heat balance is achieved. The largest cooled area of soil is

achieved by Soil 2, followed by Soils 4, 3, and 1. A similar trend is also found in the monitoring temperatures shown in Figures 4.23 and 4.24, where the highest temperature gradient is presented in Soil 2 and followed by Soils 4, 3, and 1. The possible reason is that the volumetric heat capacity of Soil 2 is significantly smaller than other soils and thus the temperature of Soil 2 is more likely reduced by a given amount of cooling energy released from the earth-sheltered building.

(a)

(b)

(c)

[C]

(d)

Figure 4.22. Temperature contours for (a) Soil 1, (b) Soil 2, (c) Soil 3, and (d) Soil 4.

(d)

(e)

Figure 4.23. (a) Schematic of monitoring points and temperatures of horizontal monitoring points for (b) Soil 1, (c) Soil 2, (d) Soil 3, and (e) Soil 4.

(a)

(b)

(c)

(d)

Figure 4.24. Temperatures of vertical monitoring points for (a) Soil 1, (b) Soil 2, (c) Soil 3, and (d) Soil 4.

The overcooling coefficients are computed as 0.30%, 0.69%, 0.31% and 0.44% for Soils 1-4 respectively. In order to demonstrate the dependence of the cooling energy

demand on the thermal properties of analyzed soils, the Pearson correlation coefficient (PCC) [114], which represents the strength of the linear association between the investigated variables, is adopted here and given by

$$r = \frac{n \sum x_i y_i - \sum x_i \sum y_i}{\sqrt{n \sum x_i^2 - (\sum x_i)^2} \sqrt{n \sum y_i^2 - (\sum y_i)^2}} \quad (4.29)$$

where n is the sample size, x_i and y_i are individual sample points indexed with i . The square of the correlation coefficients, r^2 , of zero and 1 indicate that no and perfect linear relationship exist between two variables, respectively. The PCCs between overcooling coefficients and thermal properties of analyzed soils are presented in Figure 4.25. It is indicated that the overcooling coefficient is correlated mostly to the thermal inertia, followed by the volumetric heat capacity, thermal conductivity, and thermal diffusivity. Moreover, the overcooling coefficient is proportional to the inverse of thermal inertia of analyzed soils, namely the higher the inertia, the lower the energy-saving potential. Therefore, it is the product of the volumetric heat capacity and thermal conductivity of the soil influences mostly the energy demand of the earth-sheltered building, instead of any thermal property alone. The possible reason is that the loss of cooling energy from the earth-sheltered building is effectively prevented by the surrounding soil with a small thermal conductivity, while the temperature of the surrounding soil with a low volume heat capacity is easily reduced by a given amount of cooling energy leading to a significant reduction in the heat flux from the soil to the earth-sheltered building.

Figure 4.25. Correlation coefficients between cooling coefficient and investigated soil thermal properties.

4.3.1.3 Effect of envelope thermal property

In this section, the thermal performance of the earth-sheltered building is investigated for the climate of Singapore, considering the envelope constructions of various thermal properties. The thermal resistance is adopted here to describe the heat transmit ability for the envelope construction and is given by [115]

$$R_T = R_o + R_i + \sum_{n=1}^N \frac{b_n}{k_n} \quad (4.30)$$

where R_o is the air film resistance of external surface, R_i the air film resistance of internal surface, b_n the thickness of basic material, k_n the thermal conductivity of basic material. It is noted that the air film resistance of external surface $R_o = 0$ for the earth-

sheltered building. Four types of envelope constructions [116] [117], as shown in Table 4.5, are adopted here to learn the effect on the thermal performance of the earth-sheltered building by the thermal properties of envelope materials. The investigated case studies are shown in Figure 4.26 schematically.

Figure 4.26. Schematic of the cases with envelopes of different thermal properties.

Table 4.5. Thermal properties for analyzed envelope materials.

Type	Specific heat (J/kg K)	Volumetric heat capacity (J/m ³ K)	Thermal resistance (m ² K/ W)
Envelope 1	1.080×10^3	2.592×10^6	0.259
Envelope 2	1.032×10^3	1.882×10^6	0.467
Envelope 3	1.064×10^3	1.753×10^6	0.775
Envelope 4	1.074×10^3	1.598×10^6	2.395

The simulation results are shown in Figure 4.27(a)-(d) for the surrounding soil temperature, zone air temperature, wall temperature, and heat transfer rate through the envelope, respectively. As shown in Figure 4.27(a), the surrounding soil temperatures for Envelope 1-3 drop significantly in the beginning and become consistent gradually. Meanwhile, the surrounding soil temperature for Envelope 4 decreases slightly and turns into constant quickly. Moreover, by comparing the thermal properties of analyzed envelope constructions, it is revealed that the smaller the thermal resistance is, the more the soil temperature decreases. On the other hand, reversed trends are found in Figure 4.27(b)-(d), namely the smaller the thermal resistance is, the less the zone air

temperature, wall temperature, and heat transfer rate through the envelope reduce. Probably the reason is that the envelope with a high thermal resistance effectively reduces the heat transferred from the soil into the earth-sheltered building, and hence less cooling energy is required for the earth-sheltered building.

(a) Surrounding soil temperature.

(b) Zone air temperature.

(c) Wall temperature.

(d) Heat transfer rate through envelope.

Figure 4.27. Simulation results for the cases with envelopes of different thermal properties in occupied hours.

Figure 4.28 shows the temperature contours for the four envelopes after a heat balance is achieved between the building and soil. As observed from the figure, the cooled area of surrounding soil is largest in Envelope 1 and followed by Envelope 2, Envelope 3, and Envelope 4, which means the cooled area of surrounding soil is negatively correlated with the thermal resistance of the envelope. This is possible because the cooling energy is hardly released to the surrounding soil from the earth-sheltered building with the envelope of high thermal resistance. The monitoring temperatures as functions of time t are plotted in Figures 4.29 and 4.30 for the four envelopes. The temperature gradient is shown to be the largest in Envelope 1 and decreases significantly with the increasing thermal resistance of the envelope.

(a)

Figure 4.28. Temperature contours for (a) Envelope 1, (b) Envelope 2, (c) Envelope 3, and (d) Envelope 4.

(b)

(c)

(d)

(e)

Figure 4.29. (a) Schematic of monitoring points and temperatures of horizontal monitoring points for (b) Envelope 1, (c) Envelope 2, (d) Envelope 3, and (e) Envelope 4.

(a)

(b)

(c)

(d)

Figure 4.30. Temperatures of vertical monitoring points for (a) Envelope 1, (b) Envelope 2, (c) Envelope 3, and (d) Envelope 4.

The cooling coefficients for Envelope 1-4 are computed as 0.31%, 0.72%, 1.1% and 1.7 %, respectively. The PCCs are shown in Figure 4.31 between overcooling coefficients and thermal properties of analyzed envelope constructions. As seen in the figure, the overcooling coefficient is linearly correlated to the thermal resistance, namely the higher the thermal resistance, the larger the energy-saving potential for the earth-sheltered building. Therefore, it is concluded that the application of thermal insulation materials as part of an envelope is crucial to improve the energy efficiency of earth-sheltered building, by reducing the heat transferred from the soil into the earth-sheltered building.

(a) Specific heat capacity.

(b) Volumetric heat capacity.

(c) Thermal resistance.

Figure 4.31. Correlation coefficients between cooling coefficient and envelope thermal properties.

4.3.1.4 Effect of depth

It is obvious that the depth of soil plays a significant role in the soil temperature and consequently may affect the thermal performance of earth-sheltered buildings. In accordance with Equation (2.6), the average soil temperature at any time and depth can be predicted using a sinusoidal formula shown below [58, 59],

$$T(z,t) = T_{mean} - T_{amp} e^{-z\sqrt{\pi/365\alpha}} \times \cos\left(\frac{2\pi}{365}(t-t_0 - \frac{z}{2}\sqrt{365/\pi\alpha})\right) \quad (4.31)$$

where, $T(z,t)$ is the undisturbed ground temperature at time t (day) and depth z (m), T_{mean} is the mean surface temperature (average air temperature), T_{amp} is the amplitude of surface temperature (The maximum surface temperature is $T_{mean} + T_{amp}$) and the minimum value is $T_{mean} - T_{amp}$), α is the thermal diffusivity of the soil (m^2/day), and t_0 is the day of the year with the minimum surface temperature (day).

In this section, the thermal performance of earth-sheltered buildings at the depths of 3 m, 4 m, 5 m, 6 m, 8 m, 10 m, and 12 m are examined for the climate of Singapore as schematically shown in Figure 4.32, and the corresponding annual variation of undisturbed soil temperature is shown in Figure 4.33. As seen in the figure, the temperature fluctuation decreases with the increase of the depth and becomes approximately constant when the depth $z \geq 10\text{m}$.

Figure 4.32. Schematic of the cases with various depths.

Figure 4.33. Annual undisturbed soil temperatures for various depths.

The simulation results are shown in Figure 4.34(a)-(d) for the surrounding soil temperature, zone air temperature, wall temperature, and heat transfer rate through the envelope, respectively. The temperature variation of the surrounding soil decreases with the increase of the depth as shown in Figure 4.34(a), since the surrounding soil temperature is directly influenced by the undisturbed soil temperature whose fluctuation also decreases with the increase of depth. Moreover, similar trends are found in the surrounding soil temperature, zone air temperature, wall temperature, and heat transfer rate that the greater the depth, the smaller the reduction, as illustrated in Figure 4.34(a)-(d).

(a) Surrounding soil temperature.

(b) Zone air temperature.

(c) Wall temperature.

(d) Heat transfer rate through envelope.

Figure 4.34. Simulation results for cases with various depths.

Temperature contours of the wall and surrounding soil are shown in Figure 4.35 for the cases at the end of simulation period. It is seen in Figure 4.35 that the thermal gradient is higher in the case of smaller depth. The possible reason is that the fluctuation of the

soil temperature decreases with the increase of depth and the undisturbed soil temperature tends to be constant after the depth $z = 10$ m. The temperature plots of the monitoring points as functions of time t are shown in Figures 4.36 and 4.37 for the cases. It is noted from Figure 4.37(a)-(d) that the temperatures of v_1 and v_2 fluctuate significantly with time due to the variation of the undisturbed soil temperature, while the temperatures of v_3 , v_4 and v_5 are mainly influenced by the earth-sheltered building and decrease in the first 30 days and then maintains consistent. In addition, as observed from Figure 4.37(e)-(f), the temperatures of v_1 and v_2 are almost constant due to the small variation of the undisturbed soil temperature below the depth of 8 m, while the temperatures of v_3 , v_4 and v_5 are reduced by the cooling effect of earth-sheltered building at first and then keeps constant from time $t = 30$ days when a heat balance is reached.

(a)

(b)

Figure 4.35. Temperature contours for (a) $z = 3$ m, (b) $z = 4$ m, (c) $z = 5$ m, (d) $z = 6$ m, (e) $z = 8$ m, (f) $z = 10$ m, and (g) $z = 12$ m.

(d)

(e)

(f)

(g)

(h)

Figure 4.36. (a) Schematic of monitoring points and temperatures of horizontal monitoring points for (b) $z = 3$ m, (c) 4 m, (d) 5 m, (e) 6 m, (f) 8 m, (g) 10 m, and (h) 12 m.

(a)

(b)

(c)

(d)

(e)

(f)

(g)

Figure 4.37. Temperatures of vertical monitoring points for (a) $z = 3$ m, (b) 4 m, (c) 5 m, (d) 6 m, (e) 8 m, (f) 10 m, and (g) 12 m.

In order to illustrate the effect of depth on the energy saving of earth-sheltered buildings, the overcooling coefficients σ_{oc} are computed and plotted in Figure 4.38 for various depths. It is demonstrated that, with the increase of depth, the overcooling coefficient σ_{oc} decreases rapidly when the depth $z \leq 8$ m, then the reduction becomes slowly and finally becomes zero after the depth of 10 m where the soil temperature becomes approximately constant and the same. Therefore, it is concluded that the depth significantly influences the thermal performance of an earth-sheltered building when the depth is small, and the potential energy saving for the earth-sheltered building in Singapore decreases with the increase of the depth.

Figure 4.38. Overcooling coefficient for the earth-sheltered building with different depths.

4.3.2 Energy performance by CFD-coupled energy simulation

In this section, the present CFD-coupled energy simulation is adopted to investigate the influences of key parameters on the energy consumption of earth-sheltered building. The investigated parameters include the effect of heat stored in soil, temperature set point, and climatic condition. By default, the annual ESs are conducted for the climate

of Singapore, and the depth for the earth-sheltered building is chosen as 14 m, where the undisturbed temperature of surrounding soil remains constant and equals to 28.4°C.

4.3.2.1 Effect of heat stored in soil

Considering the energy demand of earth-sheltered building, conventional ES does not take into account the effect of heat stored in surrounding soil and hence over-predicts the intake air flowrate and cooling energy. To address this problem, the present ES coupled with CFD is proposed with the supplementary information of time-varying soil temperature profile provided by transient CFD. In this section, the annual energy consumptions are compared between the earth-sheltered buildings with (Case 1) and without (Case 2) consideration of the effect of heat stored in soil and the aboveground counterpart (Case 3), as schematically shown in Figure 4.39.

(a) Case 1.

(b) Case 2.

(c) Case 3.

Figure 4.39. Schematics for the earth-sheltered building (a) with and (b) without consideration of heat stored in soil, and (c) the aboveground counterpart.

Figure 4.40. Surrounding soil and wall temperatures for earth-sheltered buildings.

The annual surrounding soil and wall temperatures achieved by transient CFD simulation are plotted in Figure 4.40 for the earth-sheltered building in scheduled and full-day operations, respectively. As seen from the figure, the temperatures for both soil and wall drop quickly at the beginning and then remain constant after a heat balance is achieved between the building and soil. The temperature contours of the two cases after thermal balance is attained are shown in Figure 4.41, where the cooled area is significantly larger in the case of full-day operation. Moreover, both the horizontal and vertical temperature gradients are higher in the case of full-day operation, compared with the case of scheduled operation, as shown in Figures 4.42 and 4.43, respectively. Probably it is because the temperature difference between the undisturbed soil and the building envelope is higher in the case with full-day air-conditioning.

Figure 4.41. Temperature contours for (a) scheduled operation and (b) full-day operation.

(c)

Figure 4.42. (a) Schematic of monitoring points and Temperatures of horizontal monitoring points for (b) scheduled operation and (c) full-day operation.

(a)

(b)

Figure 4.43. Temperatures of vertical monitoring points for (a) scheduled operation and (b) full-day operation.

By applying the time-varying and constant soil temperatures as the boundary conditions for Cases 1 and 2 respectively, the results are compared in Figure 4.44 with those of aboveground counterpart. As observed from the figure, the annual cooling energy consumptions are reduced by 12.7% and 7.2% for scheduled and full-day operations respectively, by taking into account the effect of heat stored in soil. Moreover, it is found that substantial energy savings as much as 30% and 34% are achieved for the cooling energy of earth-sheltered building in scheduled and full-day operations respectively, compared with that of the aboveground counterpart. Therefore, it becomes promising to develop earth-sheltered buildings in Singapore for energy saving, so as to consider the effect of heat stored in soil for the energy efficiency of earth-sheltered building.

(a) Scheduled operation.

(b) Full-day operation.

Figure 4.44. Comparison between the underground building with (Case 1) and without (Case 2) consideration of heat stored in soil and the aboveground counterpart (Case 3) for the annual energy consumptions.

4.3.2.2 Effect of temperature set point

Temperature set point is an essential parameter for the thermal comfort and energy cost in buildings, while its value is usually defined in a range based on the building functionality. In this section, as shown in Figure 4.45, case studies are conducted for the earth-sheltered building in full-day operation with temperature set points $T_{sp} = 16^{\circ}\text{C}$, 18°C , 20°C , 22°C , 24°C , 26°C , and 28°C , in order to demonstrate the influence of the temperature set point on the energy performance of earth-sheltered building. Moreover, the results are compared between the earth-sheltered building with (Case 1) and without (Case 2) consideration of the effect of heat stored in soil for investigated set points.

Figure 4.45. Schematic of the cases with various temperature set points.

Figure 4.46. Surrounding soil temperature for various set points.

The surrounding soil temperatures, achieved by transient CFD simulation, are shown in Figure 4.46 for various set points. With time evolution, most of the surrounding soil temperatures decrease significantly at first except that of $T_{sp} = 28^{\circ}\text{C}$. The possible reason is that the temperature of undisturbed soil is 28.4°C which is close to the set point $T_{sp} = 28^{\circ}\text{C}$ leading to a limited reduction space for the temperature of surrounding soil which reaches a heat balance with both the undisturbed soil and earth-sheltered building. The temperature contours of the seven cases after their thermal balances are attained are shown in Figure 4.47, where the cooled area of surrounding soil is found to decrease with the increasing temperature set points. Similarly, both the horizontal and vertical temperature gradients of the surrounding soil reduce with the increase of the temperature set point, as shown in Figures 4.48 and 4.49 respectively.

Figure 4.47. Temperature contours for (a-g) $T_{sp} = 16^{\circ}\text{C}$, 18°C , 20°C , 22°C , 24°C , 26°C , and 28°C .

(b)

(c)

(d)

(e)

(f)

(g)

(h)

Figure 4.48. (a) Schematic of monitoring points and temperatures of horizontal monitoring points for (b-h) $T_{sp} = 16^{\circ}\text{C}$, 18°C , 20°C , 22°C , 24°C , 26°C , and 28°C .

(a)

(b)

(c)

(d)

(e)

(f)

(g)

Figure 4.49. Temperatures of vertical monitoring points for (a-g) $T_{sp} = 16^{\circ}\text{C}$, 18°C , 20°C , 22°C , 24°C , 26°C , and 28°C .

The predicted surrounding soil temperatures are then inputted into the developed ES coupled with CFD (Case 1), and the results are compared in Figure 4.50 with that of conventional ES (Case 2). As seen in the figure, the annual cooling energy demand decreases linearly with the increasing set point of zone temperature in all cases. Moreover, with the increase of set point, the difference between Cases 1 and 2 reduces gradually from 25.18% to 0.01% for cooling energy. The possible reason is that the effect of heat stored in soil become less prominent to the earth-sheltered building with higher set points which are relatively close to the undisturbed soil temperature. It is thus concluded that the effect of heat stored in soil is necessarily taken into account for the

case with a large difference between set point and undisturbed soil temperature, in order to minimize the energy consumption.

Figure 4.50. Cooling energy of earth-sheltered buildings for various set points.

4.3.2.3 Effect of climatic condition

The present work primarily focuses on the earth-sheltered building in the tropics, predominated by summer conditions. In temperate zones, four annual seasons are ranging from warm to cool, while the frigid zones are the coldest regions on earth. Those differences among climatic conditions inevitably affect the energy performance of earth-sheltered buildings. In this section, the energy performance of earth-sheltered building in full-day operation is investigated under the climate of temperate (Shanghai, China) and frigid (Juneau, USA) zones at a buried depth $z = 3$ m to characterize the climatic variations of selected zones. The annual variations of ambient air temperature and undisturbed soil temperature at $z = 3$ m are shown in Figure 4.51(a) and (b) for Shanghai and Juneau, respectively.

(a) Shanghai, China.

(b) Juneau, USA.

Figure 4.51. Annual temperature variations of ambient air and undisturbed soil at $z = 3$ m for (a) Shanghai and (b) Juneau.

The monthly average temperatures of surrounding soil with (Case 1) and without (Case 2) consideration of the heat stored in soil are presented in Figure 4.52 (a) and (b) for Shanghai and Juneau, respectively. As observed from the figure, the surrounding soil temperature is increased by considering the heat stored in the soil for all the cases. Probably this is because the surrounding soil temperature is below the temperature set point $T_{sp} = 24^{\circ}\text{C}$ and is thus heated by the earth-sheltered building.

(a) Shanghai, China.

(b) Juneau, USA.

Figure 4.52. Surrounding soil temperature for the cases with different climatic condition.

The temperature contours of the wall and surrounding soil at the end of a year are shown in Figure 4.53(a) and (b) for Shanghai and Juneau, respectively. Similar trends for both cases are observed from Figure 4.53 that the closer the soil is to the building domain, the larger the soil temperature, because the soil is heated significantly by the building domain with a higher temperature. Using the plots of monitoring temperatures, the horizontal and vertical temperature gradients are illustrated in Figures 4.54 and 4.55, respectively. The temperature gradients for both cases increase at first and then decrease, followed by a slight rise in the end. The possible reason is that, for both cases,

the temperature of surrounding soil close to the building increases rapidly at first, and then the soil relatively far away from the building is heated up after several months by the building domain. Finally, the temperature for the soil far away from the building drops significantly due to the decreasing undisturbed soil temperature.

Figure 4.53. Temperature contours for (a) Shanghai and (b) Juneau.

(b)

(c)

Figure 4.54. (a) Schematic of monitoring points and temperatures of horizontal monitoring points for (b) Shanghai and (c) Juneau.

(a)

(b)

Figure 4.55. Temperatures of vertical monitoring points for (a) Shanghai and (b) Juneau.

Those surrounding soil temperatures are then inputted into the energy simulations as boundary conditions, and the results are compared with those of aboveground counterpart (Case 3), as shown in Figure 4.56. By comparing Case 1 with Case 2 in Figure 4.56(a), it is implied that the cooling energy is underestimated significantly by not considering the effect of heat stored in soil, as the increase of surrounding soil temperature is ignored in Case 2. Furthermore, as illustrated in Figure 4.56(a), the heating energy is completely saved in the earth-sheltered building due to the relatively high temperature of surrounding soil in the winter condition, while it contributes to 23.5% of total energy consumption in the aboveground counterpart. Consequently, the heating and cooling energy of the earth-sheltered building is 56% less than that of the aboveground counterpart. In addition, it is found in Figure 4.56(b) that the heating energy is overestimated in Case 2, because the increase of soil temperature is not considered by ignoring the heating effect from the earth-sheltered building whose space temperature is controlled to 24°C. Moreover, the heating energy is reduced by 40% in the earth-sheltered building, compared with that in the aboveground counterpart. Therefore, it is indicated that noticeable energy savings may be achieved by locating

the building underground in the investigated climatic conditions for whether cooling or heating energy.

(a) Shanghai, China.

(b) Juneau, USA.

Figure 4.56. Comparison between the underground building with (Case 1) and without (Case 2) consideration of heat stored in soil and the aboveground counterpart (Case 3) for the annual energy consumptions.

4.3.3 Control performance by full-CFD-coupled MPC simulation

In this section, case studies are conducted to evaluate the control performance of full-CFD-coupled MPC strategy under various boundary conditions. Simulations are carried out for Singapore climate at the depth $z = 14$ m.

4.3.3.1 Effect of MPC optimization on the temperature control and energy conservation of earth-sheltered building

In order to examine the influence of the proposed optimal strategy on the temperature control of earth-sheltered building, the simulation of a typical week is carried out. The set point of the zone temperature for occupied 10 hours is defined as 24°C (297.15K), and the constraint for the mass flow rate of inlet air is set as $0(\text{kg} / \text{s}) \leq \dot{m} \leq 1(\text{kg} / \text{s})$.

Figure 4.57 illustrates the heat transfer rate through the envelope of the earth-sheltered building achieved by dynamic CFD simulation in a typical week. It is noted that the first 10 hours of each day are occupied hours with air-conditioning on and other 14 hours are unoccupied hours with air-conditioning off. As observed in Figure 4.57, for each day, the heat transfer rate through the envelope rises and reaches the peak quickly when the air-conditioning is turned on, followed by a slow reduction during the occupied hours. This is probably because the heat transfer across the envelope is proportional to the temperature difference between the wall and the zone air in the earth-sheltered building. When the air-conditioning is turned on, the temperature difference rises significantly, because the zone air temperature decreases sharply and the wall temperature responds slowly. Then the temperature difference decreases slowly, while the temperature of the zone air is controlled to reach the set point and that of the wall starts to decrease. During the unoccupied hours, the temperature difference reaches zero as the zone air reaches a heat balance with the wall when the air-conditioning is off. Moreover, a decreasing trend is found in the daily heat transfer rate through the envelope, as the wall of the earth-sheltered building is cooled down by the scheduled air-conditioning system.

Figure 4.57. heat transfer rate through envelope for the earth-sheltered building in a typical week.

The Model Predictive Control (MPC) Toolbox embedded in the software MATLAB is employed here to compute the control inputs at each time step. The control inputs are then imposed to the CFD simulation as the boundary condition of mass flow inlet for the calculation of zone air temperature. The results of control input and average zone temperature are shown in Figures 4.58 and 4.59, respectively. As shown in Figure 4.58, the control inputs response closely to the fluctuation of the internal heat load, while the internal heat load is the primary heat source in the earth-sheltered building compared with the heat through the envelope. On the other hand, the observed decrease in the daily mass flow rate is attributed to the reducing heat transfer rate through the envelope. It is seen from the Figure 4.59 that, with the inlet air of which the mass flow rate is given by MPC, the average zone temperature reduces significantly during the occupied hours and reaches the set point from the second day onwards for thermal comfort in the earth-sheltered building. The result indicates that the MPC model is developed well for the optimal control of thermal performance in the earth-sheltered building. It is also

noted that the average zone temperature of the unoccupied hours drops fast on a daily basis, due to the decreasing temperature of the wall and heat storage effect of the soil.

Figure 4.58. Control input for the earth-sheltered building in a typical week.

Figure 4.59. Average zone temperature for the earth-sheltered building under the proposed optimal controller in a typical week.

After the calculation of the mass flow rate of inlet air using the present MPC controller, the time-averaged mass flow rate is obtained over a 10-hour period (occupied hours) for each day, as plotted in Figure 4.60. The corresponding wall and rock temperatures achieved by CFD simulation are shown in Figure 4.61 for the earth-sheltered building under the mass flow rate of intake air. In order to evaluate the effect of the proposed optimal control strategy on the annual energy conservation of the earth-sheltered building, the mass flow rate of the intake air for a year is required to be achieved.

However, it is observed clearly in Figure 4.60 that the daily average mass flow rate drops significantly in the first ten days and tends to be constant afterwards, which is similar to the trend of rock and wall temperatures as shown in Figure 4.61. Therefore, the mass flow rate of the inlet air is assumed consistent after the first ten days.

Figure 4.60. Time-averaged mass flow rate for the intake air in the earth-sheltered building.

Figure 4.61. Rock and wall temperatures for the earth-sheltered building under the proposed optimal control strategy.

It is well known that the lighting, equipment, and air-conditioning are the major end-use electricity consumptions for buildings. While the energy consumption of lighting and equipment are assumed the same in all cases, the difference in cooling energy, ε_c , becomes the primary source of energy conservation and is defined by

$$\varepsilon_c = \sum_{i=1}^N \frac{m_a^i - m_b^i}{m_a^i} \times 100\% \quad (4.32)$$

where m^i is the total mass flow of inlet air at the day i , and the subscripts a and b represent the cases respectively without and with the proposed optimal control strategy. The air flow rate for the case without the control system is determined based on the initial thermal load and is computed as a constant value of 0.833 kg/s. As a result, it is found in this case study that the proposed control strategy saves 13.3% of annual cooling energy in the earth-sheltered building. Probably the reason is that, with the application of the proposed control strategy, the cooling capacity of the air-conditioning system in the earth-sheltered building is controlled by adjusting the intake air flowrate to follow the dynamic load, which is decreasing considerably with time. In addition, the decrease of the thermal load is mainly due to the cooling effect on the surrounding soils, which serves as thermal mass, by the scheduled air-conditioning in the earth-sheltered building.

4.3.3.2 Effect of time-varying set point on the performance of MPC

The sensitivity to the set point is considered an important evaluation criterion for the performance of the control system. In this section, varying set points with time are assigned to the earth-sheltered building model to demonstrate how well the control system adapts to the change of set point. The set points of the zone temperature are defined as $T_{sp} = 24^\circ\text{C}$, 26°C , and 23°C for the first, second and last week respectively. The constraint for the mass flow rate of inlet air is set as $0(\text{kg} / \text{s}) \leq \dot{m} \leq 1(\text{kg} / \text{s})$.

Figure 4.62 shows the heat transfer rate through the envelope of the earth-sheltered building with varying set points. On a weekly basis, it is observed clearly from Figure 4.62 that, the maximum and minimum values of the heat transfer rate occur in the third

and second weeks, respectively. The reason may be that the heat transfer rate through the envelope is proportional to the temperature difference between the wall and the zone air in the earth-sheltered building. It is evident that the temperature difference mainly depends on the zone air temperature that is controlled to reach the set point, as the wall temperature responses much slower to the change of set point compared with the zone air. Therefore, the temperature difference reaches a maximum and a minimum during the third and second weeks, while the set points are at the lowest and highest positions respectively.

Figure 4.62. Heat transfer rate through envelope and internal heat load for the earth-sheltered building with varying set points.

Figure 4.63 presents CFD simulation results for the soil and wall temperatures in the earth-sheltered building with varying set points. In each day, the wall temperature decreases during the occupied hours and bounces back slightly during the unoccupied hours. The same trend is also found in the soil temperature but at a much smaller size. This is probably because the air-conditioning cools down the wall and surrounding soil significantly during the occupied hours. When the air-conditioning is turned off during the unoccupied hours, the wall and surrounding soil of the earth-sheltered building is heat up slightly by the far field soil at a constant temperature. Moreover, it is seen from Figure 4.63 that, the daily soil and wall temperatures decrease significantly in the first

week, then keeps almost consistent in the second week, and decrease slowly in the last week. The reason may be that the cooling effect on the wall and surrounding soil by the scheduled air-conditioning mainly depends on the temperature difference between the wall and zone air. The temperature difference between the wall and zone air reaches the peak at the beginning and decreases gradually during the first week. When the set point is changed to 26°C for the second week, the corresponding wall temperature is cooled down to 26.65°C already, as shown in Figure 4.63. Therefore, the wall temperature becomes steady during the second week due to the neglected temperature difference between the wall and zone air. By decreasing the set point to 23°C in the last week, the soil and wall temperatures decrease with the increase of temperature difference between the wall and zone air.

Figure 4.63. Soil and wall temperatures for the earth-sheltered building under proposed optimal control strategy with varying set points.

The results of control input and average zone temperature for the earth-sheltered building with varying set points are shown in Figures 4.64 and 4.65, respectively. It is observed from Figure 4.64 that the mass flow rate for the intake air reaches the bottom and peak respectively in the second and third weeks, which is inversely proportional to the trend of set points. Probably the reason is that the mass flow rate of the intake air is

proportional to the cooling load of the earth-sheltered building, and the cooling load increases with the decrease of the thermal set point. As shown in Figure 4.65, there are two edges formed in the zone temperature of each day, while the top and bottom edges represent the zone temperature respectively for the unoccupied hours and occupied hours. It is also observed in Figure 4.65 that the zone temperature responses closely to the varying set points in occupied hours, by adjusting the mass flow rate of the intake air based on the dynamic cooling load. Moreover, on a daily basis, the trend of zone temperature in unoccupied hours is found to be similar to that of wall temperature shown in Figure 4.63. Probably this is because the wall temperature makes a great contribution to the zone temperature in unoccupied hours when the air-conditioning is off. It is thus shown that the proposed MPC system adapts well to the change of set points during the optimal control of thermal performance in the earth-sheltered building.

Figure 4.64. Control input for the earth-sheltered building with varying set points.

Figure 4.65. Average zone temperature for the earth-sheltered building under the proposed optimal controller with varying set points.

4.4 Remarks

This chapter elaborates the CFD modelling, CFD-coupled energy modelling, and full-CFD-coupled MPC design for earth-sheltered buildings. In particular, a transient 2D CFD model is built up to analyze the heat flux transferred from the soil to the earth-sheltered building. The 2D CFD model is then validated by published data in the literature. It is concluded from the case studies that the surrounding soil temperature decreases with time due to the cooling effect of the scheduled air-conditioning, leading to a considerable reduction in the cooling energy required for maintaining thermal comfort in the earth-sheltered building. With the increase of depth, the energy saving potential for the earth-sheltered building decreases firstly and finally maintains constant. Moreover, among all the soil thermal properties, the energy saving potential of earth-sheltered building is the most correlated to the thermal inertia positively. In addition, the application of thermal insulation materials to envelope is crucial to improve the energy efficiency in the earth-sheltered building, by reducing the heat transferred from the soil into the earth-sheltered building.

Furthermore, a strategy coupling ES with CFD is proposed for prediction of the energy demand of earth-sheltered buildings. It is found from the case studies that the annual cooling energy consumptions for scheduled and full-day operations are reduced by 12.7% and 7.2% respectively by taking into account the effect of heat stored in soil, and the reductions are 30% and 34% compared with the aboveground counterpart. In addition, the annual energy consumption decreases linearly with the increasing set point of zone temperature. Meanwhile, the effect of heat stored in soil become less prominent to the earth-sheltered building when the temperature set point is close to the undisturbed soil temperature. Moreover, for tropic, temperate and frigid climatic conditions, significant energy savings may be achieved by locating the building underground for both cooling and heating energies.

Finally, a novel optimal strategy called full-CFD-coupled MPC, which is capable of the adaptation to the time-varying soil temperature, is proposed for the thermal control of earth-sheltered buildings. The performance of the optimal control system is examined thoroughly for the earth-sheltered building, and it is shown that the proposed control strategy saves substantial annual cooling energy for the earth-sheltered building and adapts well to the change of set points. The proposed control strategy is thus verified to be an efficient workable platform for optimal control and energy conservation of earth-sheltered buildings.

Chapter 5

Conclusions and Future Work

In this chapter, several conclusions are made in Section 5.1 from the present work, followed by a few recommendations in Section 5.2 for the possible future work.

5.1 Conclusions

Due to the increasing energy consumption and environmental impact caused by the building sector, the present research work mainly focuses on the improvement of overall energy efficiency in buildings by both active and passive strategies, namely the optimal control and earth-sheltering respectively. Based on the present work, several conclusions are detailed below.

- A novel strategy called SCFD*b*MPC is developed for the real-time optimization of thermal performance in indoor environment. Firstly, based on the two dimensional Navier-Stokes equations, a CFD model is simplified for the simulation of indoor environment, in order to significantly reduce computational cost with desired numerical accuracy. The simplified CFD model is then verified with its full CFD counterpart and integrated into the MPC algorithm to form SCFD*b*MPC system using successive linearization method. After the verification of the SCFD*b*MPC system by FLUENT simulation results, some case studies are conducted on the optimal control of thermal performance in indoor environment. The results suggest that the SCFD*b*MPC system is an efficient workable platform for optimal control and dynamic prediction of thermal distributions in indoor environment, which adapts well to

the time-varying set points, various boundary conditions, and occupant movement.

- Based on the CFD modelling analysis, the thermal performance of the earth-sheltered building is evaluated. It is concluded that the surrounding soil temperature decreases with time due to the cooling effect of the scheduled air-conditioning, leading to a considerable reduction in the cooling energy required for maintaining thermal comfort in the earth-sheltered building. With the increase of depth, the energy saving potential for the earth-sheltered building decreases at first and gradually becomes consistent. Moreover, among all the soil thermal properties, the energy saving potential of earth-sheltered building is the most positively correlated to the thermal inertia. In addition, the application of thermal insulation materials to envelope is crucial to improve the energy efficiency in the earth-sheltered building, by reducing the heat transferred from the soil into the earth-sheltered building.
- A CFD-coupled energy model is proposed for the energy prediction of earth-sheltered buildings. It is revealed from the case studies that the annual cooling energy consumptions for scheduled and full-day operations are reduced by 12.7% and 7.2% respectively by the effect of heat stored in soil, and the reductions are 30% and 34% compared with the aboveground counterpart. In addition, the annual energy consumption decreases linearly with the increasing set point of zone temperature. Moreover, when the temperature set point is close to the undisturbed soil temperature, the effect of heat stored in soil becomes less prominent on the energy performance of earth-sheltered building. Furthermore, for tropic, temperate, and frigid climatic conditions, significant energy savings

might be achieved by locating the building underground for both cooling and heating energies.

- An optimal strategy coupling full CFD with MPC is proposed for the thermal control and energy efficiency of earth-sheltered buildings, adapting with the time-varying soil temperature. Its performance is examined thoroughly through case studies, and the results show that the proposed control strategy saves substantial annual cooling energy for the earth-sheltered building and adapts well to the variation of set points. The proposed control strategy is thus verified to be an efficient workable platform for optimal control and energy conservation of earth-sheltered buildings.

5.2 Future work

The present research work has so far provided both active and passive designs for the energy saving of buildings, while it still has a long way to go towards smart and sustainable buildings. In this section, several possible interesting studies are recommended below for future work.

- Improvement on the efficiency and accuracy of SCFD_bMPC: So far, several case studies have been carried out by the SCFD_bMPC system. It is clear that much more complex grids for the CFD model would be involved in much more practical cases, since complex grids are necessary for describing the imperfectly mixing fluid fields accurately. The computational cost will inevitably be increased significantly by more controlled outputs, as well as the matrices of the proposed system. An investigation will be conducted on the efficiency and

accuracy of the model by meshing strategy with different sizes, in order to get a desired accuracy with a minimum computational cost.

- Experimental validation of SCFDbMPC: Full-scale experimental method is widely employed to validate numerical models, due to its most realistic prediction of ventilation performance in buildings. In the present work, a strategy called SCFDbMPC is developed for the real-time optimization of thermal performance in indoor environment. In order to validate the system performance, test setup will be designed and implemented in an air-conditioned environment, consisting of air-intake control units, various types of sensors, and data acquisition (DAQ) systems. Moreover, the control and monitoring of test setup will be programmed using graphical user interface (GUI) built in MATLAB. The effect of CFDbMPC algorithm on energy saving and thermal comfort will be investigated experimentally with dynamic occupancy.
- Influence of humidity gain by seepage on thermal and energy performance of earth-sheltered buildings: Seepage as the movement of water in soils is usually a critical problem for the design and performance of earth-sheltered buildings. Additional humidity due to seepage has a great influence on the latent cooling load and hence changes the sensible heat ratio in earth-sheltered buildings, which will affect the configuration of the whole air conditioning and mechanical ventilation (ACMV) system significantly, especially for the dehumidification capacity. Therefore, it will be helpful to evaluate the influence of seepage on the thermal and energy performances of earth-sheltered buildings, so as to select the most suitable ACMV system based on the sensible heat ratio.

- Application of phase change material (PCM) to the earth-sheltered building:

From the research work presented in Chapter 4, it is found that the application of thermal insulation materials as part of an envelope is crucial to improve the energy efficiency of earth-sheltered buildings. Meanwhile, PCMs have shown great potential to be incorporated into building envelopes, by absorption of substantial heat during its phase transition in a narrow temperature range to prevent heat transfer into buildings. For aboveground buildings, the efficiency of PCMs are highly restricted to the climatic condition and may only be useful in certain seasons, due to the narrow temperature range of phase transition. However, this drawback might be easily addressed by the design of deep earth-sheltered buildings, where the soil temperature maintains constant. Therefore, it will be significant to incorporate the PCMs into earth-sheltered buildings for energy saving.

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Publications Arising from the Thesis

Journal Papers

1. **Xiaoli Zhou**, Hua Li, Yeng Chai Soh, Chaoyang Jiang. *Development of Novel Strategy of Simplified Computational Fluid Dynamics Based Model Predictive Control (SCFDbMPC) for Real-time Optimization of Thermal Performance in Indoor Environment*. Building and Environment (Submitted).
2. **Xiaoli Zhou**, Hua Li, Yeng Chai Soh, Xiangyu Wu, Xiaoqin Zhang. *Development of CFD and CFD-coupled Energy Models for Earth-sheltered Buildings and Analysis of Thermal and Energy Performance*. Energy and Buildings (In preparation).
3. **Xiaoli Zhou**, Hua Li, Yeng Chai Soh. *Model Predictive Control Coupled with CFD for Optimization of Thermal Performance in Earth-sheltered Buildings*. Applied Thermal Engineering (In preparation).

Conference Papers

1. **Xiaoli Zhou**, Hua Li, Yeng Chai Soh, Chaoyang Jiang. *Development of a Novel Strategy of CFD-based Model Predictive Control*. Procedia Engineering 214 (2017): 69-75.
2. **Xiaoli Zhou**, Hua Li, Yeng Chai Soh, Chaoyang Jiang. *Development of Energy Efficient Control Strategies Based on Room Occupancy*. 9th International Conference on Materials for Advanced Technologies (ICMAT 2017), June 2017, Singapore.