Mixing enhancement in jet flow using the air tab technique

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MIXING ENHANCEMENT IN JET FLOW USING THE AIR TAB TECHNIQUE

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Mixing Enhancement In Jet Flow Using The Air Tab Technique

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ABSTRACT

It is well known that the triangular tab is an effective device to enhance jet's mixing. However, due to its protrusion nature, its blockage will induce thrust loss for the jet engine exhausts. This loss varies from 4.1% to 23.7% when the blockage area due to the tabs at the nozzle exit increases from 1.1% to 14.1% (Zaman (1999)). In the present investigation, a technique by injecting a small amount of air at certain angle of attack (AOA) into the primary jet, namely the "air tab", will be introduced. One of the advantages of this technique is that it will not cause thrust loss as the "solid triangular tab". The objective of this research is to examine the details of this air tab technique in jet's mixing experimentally and computationally.

The solid tab used for comparison in the present project is the "delta" tab, which has been shown to have the best mixing enhancement effect for the jet flow. Two configurations of the air tab have been considered for comparison with the solid tab, namely the 90° air tab and the 45° air tab defined by the angle between the air injection and the primary jet. The

primary jet is firstly operated at subsonic regime ($M_e = 0.8$). The jet's mixing enhancement effect caused by the air tab can achieve the best when the injection velocity is set at $M = 1.0$. The primary jet is subsequently changed to be at supersonic regime ($M_e = 1.3$), but the injection velocity for the air tab is maintained at $M = 1.0$. The centerline velocity decay, the variation of the axial velocity contours, the streamwise vorticity contours and the mass flux variation at successive downstream stations have been evaluated and discussed. Flow visualization has also been conducted via Schlieren technique. The experimental results reveal that the injection from the air tab is able to penetrate into the plume of the primary jet so as to shorten the jet's potential core length and to enlarge the jet's mixing region with the surrounding air as the behavior of the solid tab. A pair of inwards counter-rotating streamwise vortex is produced when either the solid tab or the air tab is used. And the 90° air tab case shows the best mixing enhancement effect among the three tabbed cases (solid tab case, 90° air tab case and 45° air tab case).

At the same time, numerical simulations of the jet's flow field by using Fluent have been performed. The simulated results shed light into the

streamwise vortices generation and their subsequent evolution which cannot be measured directly due to the limitations of the current experimental set-up. Numerical simulation results show that the streamwise vortex generated by the air tab has its origin from the same two sources as the solid tab. Source I is the upstream pressure hill formed by the blockage of the air tab to the jet. Source II is the vortex shed from the sides of the air tab. The peak value of the streamwise vortices generated by the air tab is higher than that generated by the solid tab by almost 71.4% at cross-sectional plane $x/D=1.0$. However, as the jet moving downstream, the streamwise vortices for the 90° air tab case also decays faster than that for the solid tab case. When the jet arrives at $x/D=4.0$, the difference between them becomes negligible.

Key Words: mixing, solid tab, air tab, streamwise vortices.

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NOMENCLATURE

M	Mach number at nozzle exit;
x, y, z	Cartesian coordinate system (streamwise, spanwise and traverse directions respectively), (mm);
U, V, W	Mean velocities in streamwise, spanwise and traverse directions correspondingly, (m/s);
D	Nozzle exit diameter, (mm);
b, h	Base and height dimensions of the rectangular nozzle, (m);
AR	Aspect ratio of the rectangular nozzle;
P	Pressure, (N/m ²);
ρ	Density, (kg/m ³);
ν	Kinematic viscosity coefficient, (m ² /s);
μ	Dynamic viscosity coefficient, (Kg/(s • m));
$\Omega_x, \Omega_y, \Omega_z$	Vorticity in streamwise, spanwise and traverse directions, $\vec{\Omega} = \nabla \times \vec{U}$, (1/s);
F	Thrust for the nozzle, (N);
$\dot{m}$	Mass flux for the nozzle, (kg/m ²);
A	Area for the nozzle exit, (mm ²);
θ	Angle of attack (AOA) of the tab with respect to the primary jet, (degree);
γ	Specific heat capacity ratio;
R	Gas constant, (J/(kg • k));
w, h	Base and height dimensions for the solid tab, (mm);
d	Inner diameter for the tube of the air tab, (mm);
T	Temperature, (k);
δ	Uncertainty of the corresponding item, (%);
E	Error of the corresponding item;
a	Speed of sound, (m/s);
Δ	Grid spacing in the measurement, (mm);
Vol	Volume flow rate for the air tab, (L/min);
SPL	Sound pressure level, (dB);
f	Screech frequency, (Hz);

u'_i	Velocity fluctuations in the x_i direction, (m/s);
μ_t	Eddy viscosity, (Kg/(s • m));

Subscripts

e	Nozzle exit for primary jet;
a	Ambient air;
tab	Solid tab case;
at	Air tab case;
t	Total (used in pressure and temperature);

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Chapter 1

Introduction

1.1 Background

Mixing enhancement of jet flow has been investigated extensively due to its application in the following areas: reducing the jet engine exhaust's noise in the high speed civil transport (Samimy et al. (1991)); increasing the combustion efficiency between the fuel and air (Gutmark & Grinstein (1999)); and suppressing the infra-red signature of propulsive jet plumes for military aircrafts (Knowles & Saddington (2006)).

Many approaches have been developed for the jet's mixing enhancement. Among different kinds of mixing enhancement device investigated before, tabs are found to be a simple but effective device. The most effective tab geometry (delta tab), introduced by Zaman et al. (1994), is actually a triangular-shaped protrusion with its apex leaning downstream. Two tabs are mounted to the nozzle exit diametrically. Each tab will generate a pair of counter-rotating streamwise vortices that can persist far downstream. The jet plume will be bifurcated into two halves by the action

of the streamwise vortices. And the mixing of the jet will be enhanced. The thrust loss introduced by tabs however cannot be neglected. According to Zaman (1999), the delta tabs with their blockage ratio of the nozzle exit area from 1.1% to 14.1% will lead to 4.1% to 23.7% loss of the total thrust. This penalty is significant especially for the case of jet engine.

Based on the above findings, a new technique, namely the “air tab”, is put forward in the present investigation, which is inspired by the solid tab idea. The air tab is achieved by injecting a small amount of air (comparing to the primary jet) into the jet at the nozzle exit and at a certain AOA. The injected high speed air will be able to penetrate into the primary jet plume. As the primary wraps around the air injection, the air injection will be twisted so that a pair of counter-rotating streamwise vortex is generated. By the action of the streamwise vortices, more surrounding air will be engulfed into the primary jet’s plume. Thus the mixing of the primary jet would be enhanced correspondingly. And interaction between the air injection and the primary jet will not introduce thrust loss as much as that caused by the solid tab.

1.2 Objectives

The objective of the present work is to investigate the development of the jet's flow field under the influence of the air tab via experiments and simulations. The mixing enhancement effect by the air tab and the solid tab will be compared in details.

1.3 Organization of this thesis

This thesis is organized into seven chapters.

- Chapter 1 is the introduction of this subject. Objectives and the thesis layout are also presented in this chapter.
- Chapter 2 provides the literature review on the jet's mixing with particular focus on the solid tab technique.
- Chapter 3 describes the experimental setup of this research, together with the measurement uncertainty analysis.
- Chapter 4 presents the experimental results with the primary jet set at subsonic condition ($M_e = 0.8$).

- Chapter 5 presents the experimental results with the primary jet set at supersonic condition ($M_e = 1.3$).
- Chapter 6 presents the numerical investigation of the tabs at both subsonic ($M_e = 0.8$) and supersonic condition ($M_e = 1.3$) via Computational Fluid Dynamics (CFD) by using Fluent (v6.3.26).
- The thesis is concluded in Chapter 7 with a list of suggested future work.

Chapter 2

Literature Review

2.1 Free shear layer

Since the mixing enhancement of the jet is the main objective of this investigation, it is therefore necessary to review firstly on the fundamentals of the jet's free shear layer. When the jet exits from the nozzle, a free shear layer will be formed. It is within the free shear layer that the mixing between the jet and the surrounding air will take place.

Instability is an important characteristic of the free shear layer. Disturbance introduced into a steady state free shear layer will be amplified in magnitude due to instability. Helmholtz & Kelvin were the pioneers to study the subject of instability in 1860s (Landau & Lifshits (1959)). Large-scale coherent spanwise vortices were observed over a wide range of Reynolds number (Re) in a plane free shear layer. This kind of coherent structure in the dual-jet shear layer is sketched in Fig. 2.1, together with its velocity distribution.

The development of the instability can be briefly described in the following way. The K-H instability appears when there is an inflection point existed in the velocity profile, as shown in Fig. 2.1. Consider a longitudinal strip of rotational fluid, which separates the two irrotational regions shown in Fig. 2.2(a). Supposing that this rotational zone is perturbed by a longitudinal wave, the perturbation will then be amplified. The pressure difference between the upper and lower regions will contribute to the growth of the perturbation (Fig. 2.2(b)). Together with the perturbation growing process, the peaks and the troughs of the disturbance wave will travel in the opposite direction. It will steepen the formation of the vortex sheet (Fig. 2.2(c)). Moreover, the induced velocity will modify the vortex sheet into a vortex spiral (Fig. 2.2(d)), which is commonly referred to as “Kelvin-Helmholtz cat eye”.

According to Sato (1959) and Freymuth (1966), four zones can be identified when a free shear layer becomes unstable (Fig. 2.3),

1. The place of origin of the shear layer, which is the location at which the boundary separates from the solid surface.

2. The zone at which small disturbances of the shear layer grow linearly. The disturbance can occur accidentally by environmental effects or it can be produced artificially by the acoustic perturbation from a loudspeaker or a vibrating ribbon with frequency f .
3. The zone at which the growing disturbances cause the shear layer to roll up into discrete vortices with higher harmonic frequencies $2f$, $3f$ and smaller amplitudes (Michalke (1972)).
4. The zone at which the vortices merge through “pairing”. Pairing is a process in which two adjacent vortices with the same rotation sense come closer, spin around each other, and then merge. Such “coalescence” results in the appearance of a sub-harmonic $f/2$ vortex. This successive pairing process continues until an apparent disintegration to turbulence sets in.

Besides the two-dimensional vortex structure, it has long been observed that the free shear layer also contains a well-organized array of streamwise vortices which superimpose onto the spanwise vortices (Fig. 2.4). The presence of the streamwise structure was first observed by

Konard (1976) and later by Breidenthal (1981). Bernal (1981) presented conclusive evidence that the streamwise streaks, which were previously observed in the plane views of the gas and liquid mixing layers, were actually counter-rotating pairs of axial vortices superimposed onto the spanwise structure. Jimenez (1983) confirmed Bernal's findings through a three-dimensional digital image processing of motion pictures of a plane turbulent mixing layer.

These streamwise vortices had also been stimulated by the secondary instability of the spanwise vortices. Bernal & Roshko (1986) summarized the critical characteristics in generating these streamwise vortices. These include the Reynolds number, spanwise wavelength, and the perturbation of the flow. Based on the flow visualization on the cross-sectional view in a water tunnel, a model was proposed in which the vortices were part of a single vortex winding back and forth between the high-speed side of a primary spanwise vortex and the low-speed side of the following one. Finally, they measured the distribution of the streamwise vortices along the spanwise direction. The spatial organization of the streamwise structure produced a well-defined spanwise entrainment pattern in which fluid from each stream was preferentially entrained at certain spanwise locations. At

the same time, the measurements showed that the spanwise spacing of the streamwise vortices would increase with downstream distance.

The mixing between the jet and surrounding air was eventually achieved by the existence of small-scale eddies. After the streamwise vortices were generated, the so called “*small-scale transition*” would happen due to the interaction between the streamwise vortices and the spanwise vortices. As a result, the small-scale eddies would be firstly generated near the cores of the streamwise vortices (Huang & Ho (2005), Foss & Zaman (2004)), which means that the existence of the streamwise vortices could accelerate the formation of the turbulence structure in the jet flow.

2.2 Active mixing device

Streamwise vortices can greatly enhance the mixing inside the shear layer. The mixing enhancement approaches are commonly achieved by introducing or organizing streamwise vortices in the shear layer. These approaches can generally be divided into active and passive approaches (Knowles & Saddington (2006)). In essence, active approaches, commonly referred to as perturbation method, are to generate streamwise vortices by

perturbing the flows either acoustically or mechanically (Pierrehumbert & Widnall (1982), Corcos & Sherman (1984), Corcos & Lin (1984)).

Crow & Champagne (1971) presented that introducing external acoustic excitation at preferred modes would trigger the occurrence of large scale structures. They showed that a sinusoidal surging with the amplitude of 2% of the mean exit speed imposed on the jet exit at a Strouhal number of 0.3 would enhance the jet's mixing by 32% comparing to the unforced case. They achieved the acoustic excitation by using a loudspeaker in the air supply system upstream of the nozzle and its plenum.

Zaman & Hussain (1981) used external acoustic excitations to suppress the turbulence of jets from different nozzles. Raman et al. (1989) applied the acoustic excitation to the jet with its initial turbulence intensity ranging from 0.15% to 5%, and found out that even the highest turbulence intensity jet (5%) could be influenced measurably by a tone of small amplitude. As the initial turbulence increased, the amplitude of the discrete tone had also to be increased to achieve the same excitation effects.

Lasheras et al. (1986) showed that a plane free shear layer was unstable to the introduced small perturbations in the upstream along the span. Lasheras & Choi (1988) experimentally studied that three-dimensional developments of a plane shear layer subjected to a small periodical sinusoidal perturbations. They found that the characteristic time of the growth of the two-dimensional shear instability was much shorter than that of the three-dimensional instability. During the formation of the streamwise vortex tubes, the spanwise vortices maintained their two-dimensionality, suggesting an almost uncoupled development of both instabilities in the initial stage. As the formed streamwise vortex tubes developing, the vortex tubes formed due to the three-dimensional instability would further undergo nonlinear interactions with the spanwise vortices inducing on spanwise vortices' cores a wavy undulation.

2.3 Passive mixing device

This section considers the passive devices that can be used to enhance the jet mixing. They are usually the geometric modifications to the nozzle. Three representative techniques will be briefly described below. Rectangular nozzle is a typical non-circular nozzle. Lobed mixer is the

modified lips at the nozzle exit, while tabs are protrusions attached to the nozzle exit.

2.3.1 Noncircular nozzle

Rectangular nozzle has longer perimeter when it has the same projection area as the circular nozzle. It means a larger mixing interface between the jet and surrounding air for the rectangular nozzle case. That is the fundamental reason why the mixing of rectangular jet can be enhanced with respect to the round jet. The schematics for the rectangular nozzle with varied aspect ratio (AR) are shown in Fig. 2.5.

A low aspect ratio rectangular nozzle was tested under low jet exit velocities by Quinn (1994; 1995). He revealed that the spread of jet was not uniform in its two primary planes: the minor axis spread monotonically, while the major axis decreased for the first 10-15 equivalent diameters. Quinn also found that the rate of mixing would increase with aspect ratio as long as the jet's flow field remained three-dimensional.

Tillman et al. (1991) had tested a supersonic heated rectangular jet. They presented that the centreline temperature decay for a rectangular nozzle

with aspect ratio 3.7 exhibited a potential core length shorter than that of a circular nozzle by a factor of approximately two.

Further analysis had revealed that (Zaman (1999)), comparing to the round jet, the jets ejected from the rectangular nozzle spreaded only slightly more at subsonic condition, whereas at supersonic condition, they spread much more. The dynamics of the azimuthal vortical structures of the jet, organized and intensified under the screeching condition, were thought to be responsible for the enhanced mixing at supersonic condition.

2.2.2 Lobed mixer

A more complex non-circular geometry is introduced as the form of ‘lobed mixer’ (McCormick & Bennett (1993); Belovich et al. (1996)). The schematic for the lobed mixer is shown in Fig. 2.6(a). The trailing edge can have different configurations, such as semi-circular, rectangular, triangular and sinusoidal. The parameters which affect the mixing performance are: the configuration of the trailing edge, the penetration angle and the wavelength of the lobe.

Lobed mixers are usually convoluted trailing edges designed to generate large-scale streamwise vortices between the two co-flowing streams. As shown in Fig. 2.6(b), when the oncoming streams sweep through the lobed mixer, some of the streamlines, like streamlines 1 and 2, will diverge due to the blockage effect of the lobes. After the trailing edges, streamlines 1 and 2 will twist together to form the streamwise vortices.

The application of lobed mixer has long been studied in the past, as for example, by Paterson (1984), Presz et al. (1987; 1988), Koutmos & McGuirk (1989), Tillman et al. (1991), Malecki et al. (1990), Yu (1996), Yu & Xu (1997; 1998), Yu et al. (1995; 1995; 1999; 2000), and Yu & Yip (1997a; 1997b; 1997c). Some of them will be briefly described below.

Paterson (1984) applied the lobed mixer to the nozzle exit of a turbofan engine. The obtained results suggested that the jet's mixing process was dominated by large-scale secondary circulations that were associated with strong radial velocities existed near the lobed exit plane.

Tillman et al. (1991) combined the lobed mixer with the rectangular nozzle and found out that the lobed nozzle would reduce the supersonic jet core length by about 50% comparing to a clean rectangular nozzle.

Yu (1996) investigated the flow characteristics of two types of lobed forced mixers, the un-scalloped and the scalloped mixers at velocity ratios higher than unity. Three trailing edge configurations were considered for each type of mixer, namely a square wave, a semi-circular wave and a triangular wave. The analysis revealed the importance of the strength of the streamwise vorticity shed at the trailing edge and the subsequent decaying rate in enhancing the mixing performance.

2.2.3 Tabs

Tabs can also introduce streamwise vortices to the jet flow. They are commonly referred to as vortex generators (Ahuja & Brown (1989); Zaman et al. (1994); Reeder & Samimy (1996); Zaman (1999)). A tab is a small protrusion placed at the nozzle exit which will generate a pair of counter-rotating streamwise vortices. Under the influence of the streamwise vortices, more ambient air will be engulfed into the jet's plume so as to enhance the jet's mixing process.

2.4 Solid tab technique

The original concept of the tab was brought out by accident. A screw driver placed at the nozzle exit changed Schlieren image of a supersonic jet dramatically. Furthermore, the characteristic screech tones of supersonic jet disappeared. From then on, many researchers have started to study the effect of this “accident”.

Bradbury & Khadem (1975) were among the pioneers to the study the jet flow field affected by tabs. Their investigation was conducted in subsonic jets. They compared respective configurations of tabs and found that two tabs, diametrically located at the nozzle exit, were optimum in enhancing the jet’s mixing. The jet plume was bifurcated into two parts, and the length of jet’s potential core was reduced by half. Furthermore, they predicted that the observed phenomenon was resulted from the action of the trailing vortex shedding from the tab. However, they could not verify this hypothesis. Their research was hindered by the approach and experimental method at that time.

Tanna (1977) investigated noise elimination by tabs for supersonic jets. The results showed that the azimuthal symmetry of the flow at the nozzle

exit was the basic requirement for the established feedback loop from where the screech noise came from. When the tabs were attached to the nozzle lip, this symmetry was disrupted, the feedback loop was broken down and the screech was eliminated. But his study was mainly concentrated on the noise field, and the flow field was not measured.

The most notable work in this area was done by Samimy & Zaman (1991). In addition to re-doing some of the previous experiments, they also introduced the flow visualization technique to observe the jet's spreading in cross-sectional view which was a big progress comparing to the previous work. They employed the most effective tab, delta tab, to investigate the jet's flow field (Samimy et al. (1993); Zaman et al. (1994)). The delta and simple tab are sketched in Fig. 2.7. Comparing to the simple tab, delta tab was triangular in shape and had a wider base. The tab's apex was also leaning downstream. This configuration could generate bigger streamwise vortices comparing to the simple tab. This will be discussed further in Chapter 4 and Chapter 6.

The decay for the jet's centerline pressure can indicate of the jet's mixing preliminarily. Using the delta tab, Samimy et al. (1993) measured

the supersonic jet's centerline stagnation pressure decay (Fig. 2.8). Apparently, the centerline pressure and velocity decays faster for the tabbed cases. The length of jet's potential core is also reduced almost by half by the presence of tabs. However, the centerline velocity alone is not sufficient to predict the jet spreading rate. Two diametrically located tabs will essentially bifurcate the jet plume into two cores with a narrow strip in the center linking the two cores. As a result, the centerline data of the jet in this case will overemphasize the tab's effect comparing to the free jet. The mass flux may be a more representative parameter.

Fig. 2.9 shows the mass flux variation with and without tabs. The bottom three lines correspond to the supersonic cases, while the top line is for the subsonic case. It can be seen that both the two tabs and four tabs show an increase in the jet mass flux. And the tab's effect on the mixing of the subsonic free jet is found to be more pronounced than that on the supersonic jet.

Besides the centerline velocity decay and mass flux variation, flow visualization techniques can also reveal the effect of the tab intuitively. Fig. 2.10 shows the Schlieren photographs with and without tabs at both

subsonic and supersonic conditions. For the subsonic cases, the white region indicates the jet plume. It is divided into two parts by the tabs, and the length of the visible jet plume is also reduced. For the supersonic cases, the white region indicates the locations with higher air density where shock wave has actually happened. It is commonly referred to as “Mach Disk”. With the existence of tabs, the spacing between the Mach Disks is greatly reduced and the width of the jet plume is significantly increased. All these phenomena mean that the jet’s mixing have been increased by tabs for both subsonic and supersonic conditions.

2.5 The counter-rotating streamwise vortices pair

It should be obvious that the indentation into the jet plume produced by tab is not just a wake from the tab. The previous results had shown that the indentation into the jet appeared to be growing even to the far field downstream. Fig. 2.11 shows the laser sheet illuminating the cross section of the jet at the downstream location $x/D=2.0$. All the above facts showed the existence of the streamwise vortices in the jet flow field. Zaman et al. (1994) used hot-wire anemometer to measure the velocity field of the flow and obtained the velocity distribution on the cross-sectional plane. Using the following equation:

$$\Omega_x = \left(\frac{\partial W}{\partial y} - \frac{\partial V}{\partial z} \right) \quad (2.1),$$

Zaman obtained the vorticity distribution at the cross-sectional plane $x/D=3.0$. Fig. 2.12 shows the results for no tab case, single tab case, two tabs case and four tabs case. The vorticity contours at $M=0.3$ has been normalized with respect to the jet's velocity and nozzle exit diameter. Based on the vorticity distribution, they sketched the generation of the counter-rotating streamwise vortices in Fig. 2.13.

On the other hand, it should not be forgotten that the tab's indentation into the jet can persist to the jet's far field downstream. It was conjectured that these vortices should be stationary but not periodic (Acarlar & Smith (1987)). Evidence was that the visualization images in Samimy's results were exposed with long enough time so that any periodic structure would be averaged out. Once they were formed, the streamwise vortices would interact and evolve with the spanwise vortices. As a result, the streamwise vortices distribution on a cross-sectional plane should be expected as shown in Fig. 2.14 for one and two tabs respectively. These sketched

vortices were consistent with the flow visualization results shown in Fig. 2.11.

2.5.1 Generation mechanism for the streamwise vortices

The streamwise vortex, formed over the disturbance in the boundary layer, has long been recognized as horseshoe vortex or necklace vortex (Acarlar & Smith (1987); Bandyopadhyay & Watson (1988)). And the horseshoe vortex is sketched in Fig. 2.15. However, a careful examination will reveal that the vortex presented in Fig. 2.13 is in contrast to the horseshoe vortex in rotation sense. Since the streamwise vortex produced by the tab is not the horseshoe vortex, what would be the generation mechanism behind the streamwise vortex in the tabbed cases?

Samimy et al. (1993), Zaman et al. (1994) and Reeder & Samimy (1996) analysed their experimental results and were able to summarize the two sources that were responsible for the generation of the streamwise vortices. Samimy et al. (1993) found that the tab could produce a pair of trailing vortices as that generated from the sides of a wing (Fig. 2.16), which has also been described by Van Dyke (1982). When the tabs were inserted to the nozzle exit, the approaching streamlines would be lifted up to pass by

the tab, so as to form an angle of attack of the tab with respect to the coming flow. The result was the production of a “lift” force which acted radially away from the jet axis. In this situation, the production of the streamwise vortices would be plausible. At the same time, they pointed out that the generation of these streamwise vortices should be pressure driven and inviscid phenomenon but not the wrapping of the boundary layer around the tab.

To verify the pressure differential importance in producing the streamwise vortex, Samimy et al. (1993) performed the experiment in supersonic jet with both over-expanded case and under-expanded case. It was observed that the tab’s effect was reduced in the over-expanded condition. Since the generation of the vortices was a pressure driven phenomenon, there would be favorable when a pressure jump existed across the tab. However, when the nozzle was operated in the over-expanded condition, the adverse pressure jump existing right near the nozzle lip would dilute the pressure differential formed by the tab. That should be the reason why the tab was either less efficient or ineffective under the over-expanded condition. It could also explain the phenomenon that a gap existing between the tab and the nozzle end would reduce the

tab's effect (Reeder & Zaman (1995)). Under this situation, the mixing of the ambient air and the upstream flow would also reduce the pressure differential initially formed by the tab.

In summary, Samimy et al. (1993) concluded that the streamwise vortex was generated by the pressure differential caused by the tab. However, this conclusion is insufficient. The question arises as to how exactly the pressure differential would contribute to the generation of the streamwise vortex and after it is being generated, the subsequent evolution is of equal importance.

Zaman et al. (1994) examined the previous works carefully and put forward an explanation for the generation of the streamwise vortices. Two sources of the streamwise vortices may be recognized based on the pressure gradient produced by the delta tab placed at the nozzle exit. Source I is the upstream pressure hill, which is formed by the blockage of the tab to the jet. The jet's velocity will decrease when the jet encounters the tab. Thus the static pressure will increase significantly in this area just in front of the tab. At the same time, the jet's velocity and static pressure will basically have no big change in other areas. As a result, the "pressure

hill” in front of the tab is formed. This pressure distribution is shown in Fig. 2.17. The pressure gradient in the z direction, or spanwise direction, together with the presence of the wall, will produce a pair of streamwise vortices. The vorticity flux produced by the pressure gradient in this case, assuming incompressible flow, is given by Reynolds & Carr (1985) and Panton (2005) in the following equation:

$$\frac{1}{\rho} \frac{\partial P}{\partial z} = \nu \frac{\partial \Omega_x}{\partial y} \quad (2.2).$$

The pair of vortices produced in this case would have the rotation sense as indicated in Fig. 2.18, rather than the necklace vortex. The vortices could be considered to roll down the sides of the pressure hill, as illustrated in Fig. 2.18. And the pressure hill is also a steady source producing the pair of streamwise vortices continuously.

Source II is sketched in Fig. 2.19. Sheets of vorticity shed from the sides of the delta tab, which was the same principle of the trailing vortices generated by the aircraft wing. The pressure difference between the tab’s upstream face and downstream face will become the vortex generation

source. In Fig. 2.19 the pressure distribution is located at section A-A which is cross the tab side. The pressure is shown to be slightly lower than the ambient pressure at the edges that may be expected due to streamline curvature. As a result, a vortex filament is initially formed and aligned with the side of the delta tab. As it propagates downstream, it will be reoriented by the velocity gradients, $\partial U/\partial y$ and $\partial U/\partial z$. The components Ω_y and Ω_z would be reoriented to produce Ω_x via the terms $\Omega_y \partial U/\partial y$ and $\Omega_z \partial U/\partial z$ in the vorticity transport equation (Bradshaw (1987); Potter (1982)). The 2-D view of this process is sketched in Fig. 2.20. It is obvious that the reorientation is accomplished with relatively ease in the delta tab as the vortex filament has already started with a favorable inclination. That is the reason why the delta tab configuration is optimal in generating the streamwise vortex. At last, Zaman et al. (1994) demonstrated that, between these two sources, source I was dominant.

Reeder & Samimy (1996) attempted to explain the vortex generation mechanism by the vorticity transport equation. They summarized the previous works on tab and analyzed the streamwise vortex generation mechanism systematically. Since the tab's effect presents to be the same in subsonic and supersonic jets, the source of streamwise vorticity can be

described in terms of the vorticity dynamics equation for the incompressible flow. To focus on the core of their work, the Reynolds stress terms have been omitted in the vorticity dynamics equation. In the time-averaged flow, the vorticity equation in x-direction, or streamwise direction, may be written as:

$$\begin{aligned} \frac{\partial \Omega_x}{\partial t} + U \frac{\partial \Omega_x}{\partial x} + V \frac{\partial \Omega_x}{\partial y} + W \frac{\partial \Omega_x}{\partial z} \\ = \nu \nabla^2 \Omega_x + \Omega_x \frac{\partial U}{\partial x} + \Omega_y \frac{\partial U}{\partial y} + \Omega_z \frac{\partial U}{\partial z} \end{aligned} \quad (2.3),$$

where

$$\Omega_x = \frac{\partial W}{\partial y} - \frac{\partial V}{\partial z}, \Omega_y = \frac{\partial U}{\partial z} - \frac{\partial W}{\partial x}, \Omega_z = \frac{\partial V}{\partial x} - \frac{\partial U}{\partial y}.$$

In the above equation, the pressure item has been eliminated by taking curl into the velocity transport equation. Left hand side of Eq. 2.3 is the variation of the streamwise vorticity with respect to time and space. Right hand side can be divided into three parts. First part, $\nu \nabla^2 \Omega_x$ is the viscous diffusion term. Second part, $\Omega_x \partial U / \partial x$ represents the stretching of the

streamwise vortices. Last part, $\Omega_y \partial U / \partial y + \Omega_z \partial U / \partial z$ describes the velocity gradient's production on the initial vortex. As a result, the streamwise vorticity production may be considered without reference to pressure gradient, which is in contrast to Zaman's work (1994). Of course, either route is based entirely upon the basic equations of fluid motion and can be used interchangeably. The vorticity dynamics approach is used here to provide an alternative way of understanding the formation of streamwise vortex.

Let us consider the streamwise vorticity generation Eq. 2.1. The velocity in z direction W is much greater than the velocity in y direction V at the locations adjacent to the nozzle wall. So it is reasonable to assume the streamwise vorticity can simply be represented by $\partial W / \partial y$. When the air flow comes closer to the tab, in order to pass by the tab, the flow must obtain a velocity in z direction W . Due to the no-slip condition, W should equal to 0 at the nozzle wall and increase with distance away from the nozzle wall. So $\partial W / \partial y$ should be positive. In such case, the rotation sense of the streamwise vortices should behave as that sketched in Fig. 2.14. On the other hand, the second term $\partial V / \partial z$ also has its contribution. When the tab is applied with its apex leaning downstream, $\partial V / \partial z$ will

present to be negative and contributes to the vorticity generated by $\partial W/\partial y$. However, if the tab's apex is changed to lean upstream, the term $\partial V/\partial z$ will become positive, which means that this term will generate another pair of vortices opposite to that generated by $\partial W/\partial y$ (Fig. 2.22). However, as stated before, the term $\partial V/\partial z$ is relatively smaller than the term $\partial W/\partial y$. So the inverted pair of streamwise vortices would just appear near the tab's tip and cannot turn over the overall effect. Same phenomenon has been stated by Zaman et al. (1994).

After the streamwise vorticity is generated, the evolution of the streamwise vorticity will be another important issue. Let us consider the first term $\Omega_x \partial U/\partial x$ in the right hand side of Eq. 2.3. $\Omega_x \partial U/\partial x$ actually corresponds to the vortex line stretching effect. Fig. 2.23 shows the streamwise velocity (U) distribution in the boundary layer before and after the nozzle exit. It is shown in Fig. 2.23(a) that, at the locations right near the nozzle wall, $\partial W/\partial y$ is large, while U should equal to 0 due to the no-slip condition. However, once the jet leaves the nozzle exit, as shown in Fig. 2.23(b), U will increase significantly since it is no longer restrained by the no-slip condition. This increase may not seem to be dramatic in the view of the whole jet, but it represents an order of magnitude if we consider

the regions right before and after the nozzle exit. Since both Ω_x and $\partial U/\partial x$ are prominent in this area, the vortex stretching term $\Omega_x \partial U/\partial x$ should also be prominent, which means the initial intensify of the generated streamwise vortices.

It should be noted that the last part, $\Omega_y \partial U/\partial y + \Omega_z \partial U/\partial z$, is also important in the evolution of the streamwise vortices. They correspond to the vortex line stretching effect. The explanation of this term is basically the same as Zaman's presentation (1994), which is the velocity gradient's production on the initial vortex. The components Ω_y and Ω_z would be reoriented to produce Ω_x via the terms $\Omega_y \partial U/\partial y$ and $\Omega_z \partial U/\partial z$, as shown in Fig. 2.20.

Figure 2.1 Kelvin-Helmholtz vortices in free shear layer (Lugt 1983) and its velocity distribution

Figure 2.2 Mechanism of Kelvin-Helmholtz instability (taken from <http://joas.free.fr/kelvin/sommair.htm>)

Figure 2.3 Four zones of a free shear layer (as defined by Sato 1959)

Figure 2.4 Streamwise vortices riding on spanwise vortices in plane free shear layer (taken from Wu et al. 2006)

(a) $AR=1.0$

(b) $AR=1.5$

Figure 2.5 Schematics for rectangular nozzles with varied aspect ratio

Figure 2.7 Schematics for the simple and delta tabs (taken from Zaman et al. 1994)

Figure 2.8 Centerline stagnation pressure decay for supersonic jets (taken from Samimy et al. 1993)

Figure 2.9 Mass flux variation with downstream stations (taken from Samimy et al. 1993)

Figure 2.10 Schlieren photographs for both subsonic and supersonic jets (taken from Samimy et al. 1993)

Figure 2.11 Laser sheet of the jet cross-sectional plane at $x/D=2.0$ (taken from Samimy et al. 1993)

Figure 2.12 Contours of streamwise vorticity, contour level at 0.02 (taken from Zaman et al. 1994)

Figure 2.13 Schematic for the streamwise vortex pair from tab (taken from Samimy et al. 1993)

Figure 2.14 Ideal vortex distributions for 1-tab and 2-tab cases in the cross-sectional view (taken from Samimy et al. 1993)

Figure 2.15 Schematic of horseshoe/necklace vortices (taken from Samimy et al. 1993)

Figure 2.16 Schematic of the trailing vortices (taken from Samimy et al. 1993)

Figure 2.17 Delta tab and pressure distribution upstream of the tab (taken from Zaman et al. 1994)

Figure 2.18 Schematic of vortex formation by source I (proposed by Zaman et al. 1994)

Figure 2.19 Pressure distribution across the tab (taken from Zaman et al. 1994)

Figure 2.20 Schematic of vortex formation by source II (proposed by Zaman et al. 1994)

- (a) a top view of a delta tab and the flow around it;
- (b) a front view of a delta tab with the generated spanwise velocity shown;
- (c) the sign of the vorticity generated;

Figure 2.21 Schematics of vortex generated by tabs along the tab's surface
(taken from Reeder & Samimy 1996)

Figure 2.22 Vorticity dynamics used to explain the effect of delta tab and inverted delta tab (taken from Reeder & Samimy 1996)

Figure 2.23 Increased streamwise velocity intensifies the streamwise vorticity via vortex stretching (taken from Reeder & Samimy 1996)

The pictures referred in Chapter 2 are reproduced with the permission of the corresponding authors.

Chapter 3

Experimental Set-up

3.1 Compressed air and gas supply & control system

Experiments are performed at the Fluid Dynamics Laboratory of Temasek Laboratories at the National University of Singapore.

As shown in Fig. 3.1, pressurized gas is drawn from a compressed air reservoir made up of 2 commercially available pressurized gas cylinders. Each pressurized gas cylinder has a maximum working pressure of 2,176 psig (150 bars), but they are filled only with compressed air with a pressure of 1,000 psig (approximately 69 bars). During operation, the compressed air from the cylinders passes through a series of ball valves, regulators and finally needle valve before reaching the plenum chamber with a diameter of 50mm. The needle valve allows precise adjustment of the pressure inside the plenum chamber. To monitor pressure in the plenum chamber, a pressure sensor is mounted inside the chamber to obtain the instantaneous stagnation pressure of the jet before exiting out. The plenum chamber is

lined with a series of honeycomb, perforated plates and fine screens so as to reduce the turbulence of the flow.

The nozzles are connected to the exit of the plenum chamber to generate the primary jet. For the subsonic primary jet, a convergent nozzle with the area ratio of $A/A^*=9$ and exit diameter $D=12.7$ mm has been used. In the present investigation, the exit velocity is maintained at $M_e=0.8$. For the supersonic primary jet, a convergent-divergent (CD) nozzle is applied with the same exit diameter as the convergent one. The exit velocity would be at $M_e=1.3$, i.e.

$$M_e = \left(\left((P_t/P_e)^{\frac{\gamma-1}{\gamma}} - 1 \right) \frac{2}{\gamma-1} \right)^{\frac{1}{2}} \quad (3.1)$$

where P_t and P_e are the pressure in the plenum chamber and the nozzle exit respectively. To ensure the flow is steady during operation, the stagnation pressure inside the chamber is maintained at $\pm 0.5\%$ of the theoretical stagnation pressure based on the one-dimensional isentropic flow assumption while keeping the ambient pressure fixed at 14.696 psig (1.01bar).

The compressed air for the air tab, or secondary jet, is drawn from the same source. It enters through a flowmeter, and passes into the manifold to be divided into two streams before exiting from the tube with inner diameter of $d=1.0\text{mm}$. The total flow rate for the air tab is set at 30L/min , which can guarantee that the air flow for the secondary jet will reach the choked velocity of $M=1.0$ at the tube exit.

3.2 Measurement systems

3.2.1 Pressure measurement

3.2.1.1 Pitot tube

Quantitative measurements are conducted by acquiring the pressure (and hence velocities) readings at the downstream of the jet. The aim is to construct a flow field data so as to investigate the spreading of the primary jet under the influence of tabs. A rake composed by five Pitot tubes mounted onto a 3-axis traverse gear is used to acquire pressure data in flow field. The Pitot tubes are mounted at 12.75 mm apart. Each has an opening of 1mm . Each probe is connected to a pressure transducer (Setra 280E for subsonic flow measurements; Setra 250 for supersonic flow measurements). Besides, an additional pressure transducer is mounted at

the plenum chamber to adjust the stagnation pressure inside the chamber. Raw data is acquired by using a National Instruments DAQ board (NI-PCI-6014). The velocity at each station is computed by assuming constant total temperature ($T_t=297\text{K}$) and constant ambient pressure ($P_e=14.696\text{psig}$). All pressure transducers are calibrated against $\pm 0.25\%$ of the full scale accuracy test gauge before measurements commenced. The entire testing facilities, together with the gas supply system, are shown schematically in Fig. 3.1.

3.2.1.2 Five-hole probe

Conventional Pitot tube can provide the pressure and velocity in the streamwise direction. A five-hole probe (Aeroprobe F09-34-1) has to be applied to measure the three-dimensional velocity of the flow field and hence the streamwise vorticity. This instrument extends the theory of single Pitot tube to three dimensions. During the calibration of the probe, the coefficient matrix between the five holes' pressure data and the known flow's speed and angle would be obtained. In the experiment, the five-hole probe's angular resolution can reach as high as 60° . The probe is fabricated with a conical tip, and the five holes are arranged into a "plus" formation at the tip. Each hole has its opening diameter 1.0mm. The schematic for the

five-hole probe is shown in Fig. 3.2. The probe, together with its pressure transducer, has been calibrated by its manufacturer. The max error for the five-hole probe is kept within 0.8% of velocity magnitude and 0.4° in flow angle. The probe used in the present investigation has its measurement range up to jet velocity $M=0.95$.

3.2.2 Flow visualization

Schlieren photography is used for flow visualization. The Schlieren system consists of a nano-flash lamp, a set of achromatic lenses, a circular knife edge and a digital SLR camera to capture the images. To facilitate alignment, these instruments are mounted onto traverse blocks allowing them to slide along a linear optical bench. The system is shown in Fig. 3.3.

The principle of the Schlieren photography is that the variation in the refractive index caused by the density gradients in the flow field can distort the collimated light beam. This distortion, together with the knife edge, creates a spatial variation in the intensity of light which can be directly visualized.

The two achromatic lenses have a diameter of 150 mm and a focal length of 1000 mm for collimating the light source. The nano-flash lamp sends out the light pulse with its time period 18ns recommended by its manufacturer. The images are recorded digitally with a Nikon D100 camera. During the operation, the Schlieren images are captured in a pitch-dark environment with the digital SLR set at bulb-mode, capturing only one pulse of the flash lamp. Thus the triggering of the nano-flash lamp and the DSLR camera can be synchronized manually. The exposure time for each frame is determined by the time period of a single pulse of the flash lamp, i.e. 18ns.

3.2.3 Noise field measurement

The Brüel & Kjær microphone is used to measure the far-field sound pressure spectra when the experiment is conducted in supersonic condition. The microphone is located at the exit plane of the nozzle 70D away from the jet axis and oriented at 110° with the jet's axis. The schematic for the noise measurement is shown schematically in Fig. 3.4. The same arrangement was adopted in Samimy (1991).

3.3 Initial velocity distribution and Test cases

Fig. 3.5 shows the axial velocity distributions captured by Pitot tube at the nozzle exit for both subsonic and supersonic condition. The velocity data are captured at cross-sectional plane $x/D=0.15$ along a vertical line with the grid size 0.5mm. This line is chosen to be close enough to the nozzle exit and to make sure that the probe has adequate spatial resolution. Both of the velocity distributions resemble the top-hat structure which corresponds to the jet's potential core. And the two curves are also symmetrical with the jet's centerline which is indicated by the dashed line. The velocity magnitude for the subsonic jet is at about 260m/s ($M_e=0.8$); while the velocity for the supersonic one is at about 386m/s ($M_e=1.3$). The shape factor for the subsonic jet's boundary layer is at about 3.67, while that for the supersonic one is at 2.92. The results mean that the both the subsonic and supersonic jet's boundary layers are laminar at the nozzle exit.

There are together four cases to be considered in the present investigation, as shown in Fig. 3.6. Case 1 represents the baseline jet. It is a clean jet without any disturbance from the tabs. For comparison with

tabbed cases, an attachment is mounted at the nozzle exit with extension 12mm.

Case 2 has two solid tabs attached to exit plane of the nozzle and they are 180° apart. Each tab has the dimension of $w/D=0.157$ and $h/D=0.079$. As stated in Chapter 2, the tab is mounted at angle 45° with the main flow direction and with delta shape (i.e. the apex angle is at about 90°). In such case, each tab has a projected area corresponding to 0.8% of the exit area of the primary nozzle.

Based on Zaman et al. (1994), the jet's mixing enhancement is related to the tab's base dimension (w) more than its height dimension (h). Considering the comparison of the air tab and solid tab, the injector diameter for air tab cases is arranged to be in the same order of magnitude of the solid tab's basement dimension, i.e. $d=1.0\text{mm}$. Although the air tab's inner diameter (d) seems to be smaller than the solid tab's basement dimension (w), it should not be neglected that the air flow from the air tab would expand as the jet's spreading downstream.

Case 3 has the injectors arranged in such a manner that they are injected at 90° with respect to the direction of the primary jet, which is referred to 90° air tab case. And the injectors in Case 4 are tilted at 45° with respect to the primary jet direction. The arrangement of the 90° air tab case and 45° air tab case forms a parametric study of the air tab technology.

3.4 Uncertainty analysis

In this section, the estimated uncertainties for both the Pitot tube measurement and the five-hole probe measurement will be presented.

3.4.1 Pitot tube

The Pitot tube used in the present investigation is to capture the stagnation pressure at certain point in the flow field, and hence to obtain the corresponding time-averaged streamwise velocity. Based on the obtained velocities, the mass-flux of the jet is calculated by the integration of the streamwise velocity with respect to the cross-sectional area. Consequently, the uncertainty analysis would be performed on the velocity measurement, and the mass-flux measurement.

3.4.1.1 Uncertainty of Pitot tube system

Theoretically, the uncertainty for the stagnation pressure measured by Pitot tube originates from three parts. The first part is from the measurement resolution. The second part is the random fluctuation, and the last part is the systematic error. In the actual measurement, the pressure is not directly read from the pressure gauge, but from the data acquisition system and presents as digital signals in a computer. So the measurement resolution error can be included into the measurement system error (Fornasini (2008)).

The systematic error of Pitot tube is made up from probe disturbance and vibration, pressure transducer and data acquisition, and the noise from the circumstances. The error arising from the probe disturbance can be negligible, because the nozzle exit diameter used in the present experiment is at $D=12.7\text{mm}$ while the opening for the probe is at $d=1.0\text{mm}$. It means that the probe disturbance is much smaller comparing to the jet characteristic length (i.e. nozzle exit diameter). On the other hand, the Pitot probes are mounted onto a rake which is fixed at the traverse gear system. The vibration caused by the probe should be very small. Thus this error is not taken into consideration.

The sampling frequency of Pitot tube is set at 1kHz, which should be enough for capturing the required pressure signal without considering the turbulent effect. The output voltage of the pressure transducer (Setra series) has a range of 0-5 volts, and the 16-bit NI-PCI-6014 board has a resolution of $54.2\mu\text{V}$. So the error caused from the pressure transducer and data acquisition system could also be negligible.

Finally, the experiment is conducted in a confined space, which is decorated by wedge-shaped foam material attached to the inner wall. The reflection of the sound wave would be eliminated as much as possible. So the noise from the circumstance is also not taken into consideration. Therefore, the systematic error for the Pitot tube could be negligible.

3.4.1.2 Uncertainty of the measured pressure

Excluding the systematic error, the random fluctuation will be taken into consideration for the analysis of the pressure's uncertainty.

There are totally $N=1000$ samples to be captured for each pressure. The error for a single sample comes from the instability of the pressure in the

plenum chamber, which is estimated to be within $\pm 1\%$. The error from the random fluctuation for the pressure would therefore be:

$$\begin{aligned}\delta P_{cas} &= \sqrt{\frac{1}{N(N-1)} \sum_{i=1}^N (P_i - \bar{P})^2} \\ &= \sqrt{\frac{1}{1000 \cdot 999} \times 1000 \times 1\%^2} = 0.031\%\end{aligned}\tag{3.2}.$$

This error has its confidence level at 68%. To improve the confidence level to 99% in the present experiment, the error will become $3\delta P_{cas}$, i.e. 0.093%.

3.4.1.3 Uncertainty of the velocity

The velocity in the flow field is calculated based on the one-dimensional isentropic flow assumption. The calculation process is:

$$\frac{P}{P_a} = \left(1 + \frac{\gamma - 1}{\gamma} M^2\right)^{\frac{\gamma}{\gamma - 1}}\tag{3.3},$$

so

$$M = \left(\left(\frac{P}{P_a} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right) \frac{2}{\gamma-1} \right)^{\frac{1}{2}} \quad (3.4).$$

On the other hand,

$$\frac{T}{T_t} = \left(1 + \frac{\gamma-1}{2} M^2 \right)^{-1} \quad (3.5)$$

then

$$a = \sqrt{\gamma \cdot R \cdot T} = \sqrt{\gamma \cdot R \cdot T_t \cdot \left(1 + \frac{\gamma-1}{2} M^2 \right)^{-1}} \quad (3.6).$$

As a result, the velocity on a certain grid point would be:

$$U = M \cdot a = \sqrt{\frac{2}{\gamma-1} \left(\left(\frac{P}{P_a} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right) \cdot \gamma R T_t \frac{1}{1 + \frac{\gamma-1}{2} M^2}} \quad (3.7).$$

$$= \sqrt{\frac{2\gamma RT_t}{\gamma - 1} \left(1 - \left(\frac{P}{P_a}\right)^{\frac{1-\gamma}{\gamma}}\right)}$$

For the present investigation, P is the measured stagnation pressure, as stated earlier, P_a is the ambient static pressure, T_t is the total temperature in the plenum chamber, R ($= 287.06(\text{J/Kg}\cdot\text{K})$) is the gas constant, γ ($=1.4$) is the specific heat ratio. The error for the constants R and γ should be negligible, and the error for P_a and T_t comes from the measurement resolution, i.e.

$$\begin{aligned} E_{T_t} &= 0.5K; \\ E_{P_a} &= 0.5\text{psi}; \end{aligned} \tag{3.8}$$

thus,

$$\begin{aligned} \delta T_t &= \frac{E_{T_t}}{T_t} \approx 0.017\%; \\ \delta P_a &= \frac{E_{P_a}}{P_a} \approx 0.034\%. \end{aligned} \tag{3.9}.$$

So the uncertainty for the velocity measured by the Pitot tube would be:

$$\begin{aligned}
 \delta U &= \left(\left(\frac{\partial U}{\partial T_t} \cdot \delta T_t \right)^2 + \left(\frac{\partial U}{\partial P} \cdot \delta P \right)^2 + \left(\frac{\partial U}{\partial P_a} \cdot \delta P_a \right)^2 \right)^{\frac{1}{2}} \\
 &= \sqrt{(0.44 \times 0.017\%)^2 + (13 \times 0.093\%)^2 + (20 \times 0.034\%)^2} \\
 &= 1.4\%
 \end{aligned} \tag{3.10}.$$

3.4.1.4 Uncertainty of the mass flux

The mass flux is obtained by integrating the streamwise velocity with respect to local the cross-sectional plane. However, the actual calculation of the mass flux is quite difficult as Crow & Champagne (1971) have stated that “*the notions of volume flux and entrainment are creatures of theory, in the case of a jet, rather than experiment*”. And Zaman (1999) complemented that “*the integrand does not fall off to zero in the surrounding potential flow region and the volume flux in the induced potential flow is infinite. Both hot-wire and Pitot probe measurements involve errors on the periphery of the jet owing to large turbulence and flow angularity*”. Based on the above fact, Zaman truncated the region in the integration from where the streamwise velocity falls below 1% of the local centerline velocity and obtained an acceptable repeatability of the mass flux. In the present investigation, same truncation criterion has been applied to the mass flux calculation. As a result, the mass flux obtained in

the present experiment should be considered as nominal. However, the uncertainty for the “nominal” mass flux could still be estimated.

The equation for calculating the mass flux is:

$$\dot{m} = \int \rho U dx dy \quad (3.11).$$

Here both dx and dy (represented by Δ_1) are at 2.05mm, the measurement resolution error for Δ_1 is:

$$E_{\Delta_1} = 0.01mm \quad (3.12).$$

Thus

$$\delta\Delta_1 = \frac{E_{\Delta_1}}{\Delta_1} = 0.5\% \quad (3.13).$$

On the other hand,

$$\frac{\rho}{\rho_t} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{-1}{\gamma - 1}} \quad (3.14).$$

According to the ideal gas law equation,

$$\rho_t = \frac{P_t}{RT_t} \quad (3.15),$$

and

$$M = \frac{U}{a} = \frac{U}{\sqrt{\gamma RT}} \quad (3.16).$$

Since the total pressure is monitored through a pressure sensor amounted inside the plenum chamber and adjusted manually to be within $\pm 0.5\%$ of the required value. So the error for the total density should be:

$$\delta \rho_t = \left(\left(\frac{\partial \rho_t}{\partial P_t} \cdot \delta P_t \right)^2 + \left(\frac{\partial \rho_t}{\partial T_t} \cdot \delta T_t \right)^2 \right)^{\frac{1}{2}} = 0.0012\% \quad (3.17).$$

On the other hand, the value of the error for M is calculated to be at about $\delta M = 0.15\%$.

So the error for the density is at:

$$\delta \rho = ((\frac{\partial \rho}{\partial \rho_t} \cdot \delta \rho_t)^2 + (\frac{\partial \rho}{\partial M} \cdot \delta M)^2)^{\frac{1}{2}} \quad (3.18).$$

Given the subsonic condition $M_e = 0.8$, the error $\delta \rho$ would be at 0.038%.

So the uncertainty for the mass flux would be:

$$\delta \dot{m} = ((\frac{\partial \dot{m}}{\partial \rho} \cdot \delta \rho)^2 + (\frac{\partial \dot{m}}{\partial U} \cdot \delta U)^2 + (\frac{\partial \dot{m}}{\partial \Delta_1} \cdot \delta \Delta_1)^2)^{\frac{1}{2}} \quad (3.19),$$

which equals to 5.2%.

3.4.2 Five-hole probe

The velocity measured by the five-hole probe has its uncertainty of 0.8%, which has been indicated by the manufacturer.

3.4.2.1 Uncertainty of the streamwise vorticity

The vorticity is obtained by taking curl into the velocity, which is:

$$\vec{\Omega} = \nabla \times \vec{V} \quad (3.20).$$

For the Cartesian coordinate system, the above equation would be

$$\vec{\Omega} = \begin{vmatrix} i & j & k \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ U & V & W \end{vmatrix} \quad (3.21).$$

Correspondingly, the streamwise vorticity is

$$\Omega_x = \left(\frac{\partial W}{\partial y} - \frac{\partial V}{\partial z} \right) \cdot i \quad (3.22).$$

Using the Taylor hypothesis, it can be simplified to be

$$\Omega_x \approx \frac{\Delta W}{\Delta y} - \frac{\Delta V}{\Delta z} \quad (3.23).$$

Refer to Fig. 3.7, for the point (i, j) , the streamwise vorticity is calculated as follows:

$$\Omega_x(i, j) \approx \frac{W(i, j+1) - W(i, j-1)}{2\Delta y} - \frac{V(i-1, j) - V(i+1, j)}{2\Delta z} \quad (3.24).$$

In the above equation, Δy and Δz (represented by Δ_2) are both at 2.0mm. The measurement resolution error for E_{Δ_2} is 0.01mm. So the relative error for Δ_2 is:

$$\delta\Delta_2 = \frac{E_{\Delta_2}}{\Delta_2} = 0.5\% \quad (3.25).$$

The uncertainty for the local vorticity is:

$$\delta\Omega = \sqrt{4 \cdot (\delta U)^2 + \delta\Delta_2^2} = 2.8\% \quad (3.26).$$

As a summary, the uncertainties for the measured quantities have been listed out in Table 3-1.

Item	Uncertainty
Gauge Pressure (P)	$\delta P = 0.093\%$
Velocity (U) (measured by Pitot tube)	$\delta U = 1.4\%$
Mass Flux ($\dot{m}$)	$\delta \dot{m} = 5.2\%$
Velocity (U) (measured by five-hole probe)	$\delta U = 0.8\%$
Streamwise Vorticity (Ω)	$\delta \Omega = 2.8\%$

Table 3-1 Uncertainties of the measured quantities

Figure 3.1 Schematic of gas supply system and the pressure measurement

Figure 3.2 Schematic of the five-hole probe

Figure 3.3 Schematic of Schlieren photography arrangement

Figure 3.4 Schematic for the noise field measurement

Figure 3.5 Axial velocity distributions at the nozzle exit for both subsonic and supersonic

(a) Free jet (case 1)

(b) Solid tab (case 2)

(c) 90° airtab (case 3)

(d) 45° airtab (case 4)

Figure 3.6 Tab configurations under investigation (All dimension are in mm)

Figure 3.7 Schematic diagram for the streamwise vorticity measurement grids, $\Delta y = \Delta z = 2.0mm$

Chapter 4

Experimental results: primary jet flow at subsonic condition ($M_e = 0.8$)

4.1 Introduction

As stated in Chapter 2, the solid tab is a simple and effective passive mixing device. When the tabs are mounted at the trailing edge of the nozzle exit with appropriate geometry, they would generate counter-rotating streamwise vortex pair which can distort the jet cross-section shape and increased the jet spreading rate significantly. The streamwise vortices, generated by the tabs or vortex generators, tended to persist over many jet diameters downstream once being generated in the flow. Zaman (1999) conducted a systematic test on a series of nozzles with various shapes and found that the spreading of most asymmetric jets was not much different from that of a round jet, but the biggest increase in jet spreading was observed with the tabs. However, the penalty of introducing the tabs was also found to be significant. The thrust lost due to the tabs varied from 4.1 to 23.7 percent when the flow blockage (proportional to the projected area of tabs) increased from 1.1 to 14.1 percent.

To minimize the thrust lost caused by tabs, but yet to maintain its effectiveness in mixing enhancement is important to many practical applications. Many researchers have been searching for the new techniques with better effects on mixing but minimum penalty on thrust. Zaman et al. (1994) compared various tab geometries and they found that the delta tab had the most pronounced effect at the same area blockage. Zaman & Raman (1997) combined the tab technique with acoustic excitation. Two electro pneumatic drivers were employed to impart the excitation. Two delta tabs were placed along the nozzle trailing edge with the apex leaning downstream at an angle of 135° . However, this combination led to the reduction in jet spreading due to the opposite effects between lateral spreading of the streamwise vortex pairs introduced by tabs and the distorted coherent azimuthal structure produced by excitation. Bohl & Foss (1999) used primary tab and secondary tab to enhance the outward directed flow from the jet's core region. The secondary tab was placed next to but pointed away from the primary tab. They found strong mixing enhancement when the primary tab and secondary tab were optimally oriented. However, those optimized tabs can decrease the penalty on thrust only to a very limited extent. Similar results were also found by Yu & Hou (1998).

This chapter presents results which show minimum or no impact on thrust, but it would be able to provide significant effect as the solid tab on mixing enhancement. The rationale of the so-called air tab technique will be presented. The experiments were performed at primary jet velocity at $M_e = 0.8$. It will be followed by the theoretical analysis of the thrust and presentation of results. The chapter ends with brief concluding remark.

4.2 Consideration of thrust

Although the solid tab technique can significantly improve the spreading of the jet flow, it will still cause reduction in the jet's thrust. Assuming one-dimensional flow at the nozzle exit, the thrust F of an exhaust nozzle is given by:

$$F = \dot{m}U_e + (P_e - P_a)A_e \quad (4.1),$$

here, $\dot{m}$ is the mass flux from the exhaust nozzle, U_e and P_e are the velocity and pressure at the nozzle exit, A_e is the area of the nozzle exit, and P_a is the ambient pressure.

Since $\dot{m}U_e \gg (P_e - P_a)A_e$ (at the ideal condition, $(P_e - P_a)A_e = 0$), the thrust for an exhaust nozzle will be:

$$F \cong \dot{m}U_e \quad (4.2),$$

here, $\dot{m} = \rho_e U_e (A_e - kA_{tab})$, A_{tab} is the blockage area of the tab, k is a coefficient which is usually larger than 1. Zaman et al. (1996) attributed it to the streamline's distortion caused by the tab. His results showed that a single tab with its projection area 1.5% of the nozzle exit area will lead to 3% loss of the total thrust.

By replacing the solid structure with a virtual one, the situation will be changed. The air tab technique is therefore designed, and it is achieved by injecting a small amount of air into the primary jet plume at certain attacking angle. Similar to the solid tab, the air tab will also block the emitting gas, generate the streamwise vortices and improve the spreading of the primary jet significantly. However, the air tab will not introduce the thrust penalty for the jet. That is because the injected air will finally be diverted to align with the primary flow's direction. Thus, it will eventually contribute to the total thrust.

However, in practical applications, the high-pressure air from the air tab would likely be tapped from the compressor of an aero-engine. The compressed air tapped from the compressor will still reduce the amount of exhaust gas discharged from exhaust nozzle, resulting in thrust reduction. The consideration of the thrust affected by the air tab will be in the following.

The thrust is proportional to the mass flow rate. If the air tab takes 2 percent of the air from the compressor, then the thrust loss at nozzle exit is about 2 percent and the total thrust becomes:

$$F_{tab-nozzle} \cong 0.98\dot{m}U_e \quad (4.3).$$

The 2 percent of air for the air tab would not be wasted, as the high speed air injection of the air tab will also make its contribution into the thrust. The thrust from an air tab (denoted by the subscript “at”) is given by:

$$F_{at} = \dot{m}_{at}U_{at} + (P_{at} - P_a)A_{at} \cong \dot{m}_{at}U_{at} \quad (4.4).$$

Contribution to the thrust of the primary jet will be:

$$F_{at} = \dot{m}_{at}U_{at} \cos \theta \quad (4.5),$$

here, θ is the attacking angle of the air tab. If $\theta = 45^\circ$, and the amount of ejection air is 2 percent of the primary jet: $\dot{m}_{at} = 0.02\dot{m}$, then

$$F_{at} = \dot{m}_{at}U_{at} \cos \theta = 0.02\dot{m}U_{at} \times 0.707 = 0.01414\dot{m}U_{at} \quad (4.6),$$

if $U_{at} = 1.5U_e$

$$F_{at} \approx 0.02\dot{m}U_e \quad (4.7).$$

The total thrust for the exhaust nozzle is:

$$F_{total} = F_{tab-nozzle} + F_{at} = 0.98\dot{m}U_e + 0.02\dot{m}U_e = \dot{m}U_e \quad (4.8).$$

The above derivation means that there is no thrust loss caused by the air tab. It is obvious that the air tab technique would not cause large penalty on the thrust if the injector has higher velocity than the jet itself, especially when the exit velocity for the air tab is no less 1.5 times of the primary jet's velocity.

4.3 Experimental results

4.3.1 Centreline velocity decay

The jet's centreline velocities are obtained from the Pitot tube measurements. The measuring points start from $x/D=0.5$ until $x/D=26$ with a step of $0.5D$. As stated earlier, the centreline velocity decay of the jet can provide preliminary information about the jet's mixing characteristics. In other words, the faster the jet's velocity decays, the greater the jet's mixing will be.

Fig 4.1 shows the variation of the jet's centreline velocity with respect to the normalized downstream distance for the four respective cases. It can be seen that the free jet (case 1) maintains its exit velocity to about 5 diameters (D) downstream. It means that the length of the jet's potential

core is at about $5D$. It is immediately followed by a rapid velocity decay which should be attributed to the rolled up of the large scale Kelvin-Helmholtz type of vortices. In the rapid decay region, the velocity decay rate (decay slope of the curve fitting to the discrete points) with respect to the x axis is estimated to be at about -0.6. The calculation is conducted by fitting the data between $x/D=5.0$ and $x/D=14.0$. This decay rate agrees well with the results obtained by Zaman et al. (1996), but his experiment was performed at $Me = 0.3$.

The solid tab (case 2) and the 45° air tab (case 4) have reduced the jet's potential core to less than $2D$. The 90° air tab (case 3) shows the shortest potential core. At the same time, the subsequent velocity decay rate after the potential core for case 3 is found to be the highest among the three tabbed cases. The possible reason for this phenomenon could be that the two opposite injections of the 90° air tab case could impinge onto each other so as to produce a backward flow against the primary jet right near the nozzle exit. However, as the jet spreads downstream, the difference between these three tabbed cases has been eliminated by the viscosity dissipation.

To investigate the impact of the air tab's injection velocity on the primary jet, a systematic study is performed. Fig 4.2 shows the centreline velocity decay for different injection Mach number for the 90° air tab case (case 3). The variation of the injection's velocity is achieved by controlling of the flow upstream of the air injection. Three cases had been tested, which were: $M = 0.6$, $M = 0.8$ and $M = 1.0$. It is shown in Fig 4.2 that the length of the potential cores as well as the subsequent decay rate were found to be shortened and enhanced with the corresponding increase in injection velocity until $M = 1.0$. It is noted that, when the air injection's velocity achieves at the same velocity as the primary jet ($Me = 0.8$), the acceleration effect for the centreline velocity decay starts to become apparently. Furthermore, when the air injection's velocity reaches $M = 1.0$, the potential core of the primary jet almost disappears. Since the effect of the air tab at $M = 1.0$ is the most pronounced one, the subsequent experiments for the comparison between air tab and solid tab are all performed under this condition.

4.3.2 Flow visualization results

Fig 4.3 shows the Schlieren pictures for the four respective cases. The pictures were captured in the way that the light beam was perpendicular

to the plane containing the tab's centreline. It can be identified from the schematics of the tab at the upper left of the picture. In each picture, the boundary between the jet and surrounding air has roughly been indicated by the superimposed black lines.

In Fig 4.3(a) and case 1, the distribution of the grain pattern inside the potential core suggests that the velocities within this region are uniformly distributed. The mixing between the jet and the surrounding air has only become obvious from about $x/D=5.0$ onward. This result is agreeable with the centreline velocity distribution shown earlier (Fig. 4.1).

In Fig 4.3(b), after the tabs are attached onto the nozzle exit, the length of the jet's potential core is found to be reduced by almost 50%, and the intense mixing between the jet and the surrounding air has become obvious starting from the nozzle exit plane. The spread of the jet is also found to be somewhat wider than the free jet.

In Fig 4.3(c) and case 3, the jet's potential core is even shorter than case 2. Meanwhile, the jagged edges at the jet plume boundaries appears immediately after the jet is discharged from the nozzle, which indicates

faster and earlier mixing between the jet and the surrounding air comparing to that shown in Fig 4.3(a) (case 1) and 4.3(b) (case 2).

Fig 4.3(d) shows the case when the injector is orientated at 45° with respect to the primary jet (case 4). In this image, the plume of the injected air can be clearly identified, which should be due to its pressure difference with the primary jet. It is also noted that the length of the jet's potential core for case 4 is almost the same as that for case 2, and that the potential core lengths for both case 2 and case 4 are a little longer than that of case 3.

The above flow visualization results have demonstrated intuitively that only a small amount of air injection to the primary jet can effectively shorten the jet's potential core and enlarge the mixing region significantly. It will be further quantified by the cross-sectional velocity contours and mass flux variation in the following sections.

4.3.3 Velocities contours at successive downstream locations

Fig 4.4 shows the normalized velocity contours at successive downstream locations. The measured velocity at each point has been

normalized by the jet exit velocity U_e . The overall sampling area is 60mm x 60mm in the cross sectional plane (y-z plane) for the near field measurement and increases to 120mm x 120mm for the far field measurement. As stated earlier, the grid size is set at $\Delta_1 = 2.05$ mm. A total of 4 planes ($x/D = 4.0, 6.0, 10.0$ and 18.0) are measured for each case.

The effect of the tabs on the jet's spreading in the lateral direction can be readily appreciated. At stations closer to the nozzle exit plane, e.g. $x/D=4.0$, both the solid tab and the air tab can bifurcate the primary jet into a kidney shape with two potential cores located symmetrically about the jet's centreline. This observation is agreeable with Zaman's result (1994). Comparing to the free jet case, the primary jet under the effect of the tabs is compressed so as to spread only in y direction. It is shown in the Fig 4.4 that the extent of the velocity contours for the tabbed cases is wider than that of the free jet in y direction. This result should be due to the action of the streamwise vortices generated by tabs. The extension of the velocity contours in y direction results in the fact that the mixing area between the primary jet and the surrounding air will be increased, and hence, the enhanced mixing of the primary jet with the surrounding air.

On the other hand, the three tabbed cases (case 2, case 3 and case 4) almost show the extension of the velocity contours in the y direction in the same order of magnitude.

Lastly, as the jet spreads downstream, the kidney shape structure is gradually weakened by viscosity diffusion. At $x/D=4.0$, this structure is the most pronounced. When the jet arrives at $x/D=18.0$, the kidney shape structure has almost vanished and is replaced by an elliptical contours. This can be attributed to the decay of the streamwise vortices. The generation and the evolution of the streamwise vortices will be discussed in the following section.

4.3.4 Mass flux distribution

Fig 4.5 shows the mass flux variation with downstream distance for respective cases. As stated in Chapter 3, the mass flux is obtained by integrating the streamwise velocity with respect to the local cross sectional area. The mass flux presented in Fig 4.5 has been normalized by the jet mass flux at nozzle exit $\dot{m}_e$.

There are 4 planes ($x/D= 4.0, 6.0, 10.0$ and 18.0) to be measured for the mass flux. As shown, the rate of increase for the free jet varies almost linearly with downstream distance. The tabs have significantly increased the entrainment rate by almost 30%. For case 3 and case 4, the rates of increase for both cases are nearly the same as the solid tab case (to be within 5%).

4.3.5 Discussion of the streamwise vortices

It is obvious that the indentation into the primary jet produced by the tabs is not simply a wake phenomenon. As stated in Chapter 2, Zaman et al. (1994) used the hot-wire anemometer to measure the velocity field of the jet flow, obtained the velocities (V, W) in y and z directions and calculated the streamwise vortices $\Omega_x = (\partial W / \partial y - \partial V / \partial z)$ at certain cross-sectional plane. In the following section, the streamwise vortices measured by the five-hole probe will be presented.

Considering the fact that there should be adequate spatial resolution and the strength of the streamwise vortices needs to be measurable, the cross-sectional plane $x/D=2.0$ is chosen for the investigation. As mentioned in Chapter 3, the grid density on the plane is set at $\Delta_2=$

2.0mm. The presented vorticity has been normalized by U_e/D , while the velocity has been normalized by U_e .

The measured streamwise vorticity contours, together with the normalized streamwise velocity, at cross-sectional plane $x/D=2.0$ are shown in Fig. 4.6. In each figure, the outlines of the nozzle exit and the tabs have been incorporated. Left hand side shows the velocity contours while the right hand side corresponds to the streamwise vorticity contours. In all the figures, two pairs of counter-rotating streamwise vortices, generated by the tabs, can be clearly observed. For clarification, solid lines indicate the rotation sense in the counterclockwise direction, while dashed lines are for the rotation sense in the clockwise direction.

In Fig. 4.6(a) and case 2, the highest value for the streamwise vortices Ω_x is estimated to be at about 0.4. According to the experimental results by Zaman et al. (1994), the streamwise vortices' peak value for the solid tab at $x/D=2.0$ was at about 0.24. His measurement was conducted by the hot-wire anemometer at $Me = 0.3$. Considering the error in the measurement and calculation, the two results are basically at the same order of magnitude. This observation suggests that the generation of the

streamwise vortices is not significantly affected by the primary jet's velocity, or the compressibility characteristics of the primary jet. In Fig. 4.6(b) and case 3, the streamwise vortices' peak value has increased to 0.65. For Fig. 4.6(c) and case 4, the peak value for the streamwise vortices is between case 3 and case 2, i.e. at about 0.5.

Another difference about the streamwise vortices between the solid tab case and the air tab cases lies in the location of the streamwise vortices. For case 2, the core of the streamwise vortices appears at the region where the local velocity is at about $U/U_e = 0.1$. This means that the streamwise vortices are staying at the outer area of the mixing layer. For case 3 and case 4, the streamwise vortices locate at the region where the local velocity is at about $U/U_e = 0.5$. The comparison between the solid tab case (case 2) and the air tab cases (case 3 and 4) indicates that the injection from the air tab can penetrate deeper into the primary jet comparing to the solid tab.

4.3.5.1 Generation mechanism for the streamwise vortices

The comparison of the streamwise vortices generation mechanism between solid tab and air tab will be discussed in this section. The

streamwise vortices generation mechanism for the solid tab case has already been discussed in details in Chapter 2, and will only be briefly described here. The streamwise vortices generated by the solid tab come from two sources. The first source is the pressure gradient in the z direction upstream of the solid tab, which functions together with the presence of the nozzle inner wall to produce the streamwise vortices. This process may be expressed by Eq. (4.2). The pressure gradient is caused by the blockage effect of the solid tab.

$$\frac{\partial P}{\partial z} = \mu \frac{\partial \Omega_x}{\partial y} \quad (4.2)$$

The second source originates from the vortex shed from the tab's side. As the jet spreads downstream, it would be reoriented by the velocity gradients in the shear layer to become streamwise. It should be noted that the first source is usually the dominant one. These two sources contribute together to produce the streamwise vortices. The flow is sketched schematically in Fig. 4.7(a).

For the streamwise vortices generated by the air tab, the primary jet would be found to decelerate near the upstream surface of the air tab injection and thus construct a positive pressure region. The pressure difference between the upstream surface and downstream surface of the air injection would cause a lateral deflection of the primary jet flow, which is similar to the airflow passing by a solid cylinder. The effect of the lateral deflection would result in a pair of counter-rotating vortices initially appearing just behind the injected stream, and gradually changing the cross section of the injected stream from circle to a characteristic kidney shape as the momentum of the injected air decreases. The evolution of the injected air stream is sketched from cross-sectional view A to cross-sectional view B. At the same time, through the entrainment effect of the counter-rotating vortices, part of primary jet which surrounds the air injection will also be engulfed into the vortices. The relatively higher momentum of the primary jet causes the injected air stream to be aligned with the primary jet and thus, the pair of counter-rotation vortices will eventually become streamwise. The airflow for the air tab case is sketched in Fig. 4.7(b).

4.4 Summary

Based on the above observation and analysis, some concluding remarks can be made. When the primary jet is running at its subsonic regime ($Me = 0.8$), both the solid tab and the air tab can enhance the jet's mixing to some degree.

As the tabs are attached to nozzle exit, the primary jet's potential core will be shortened by at least 50% and then the decay for the jet's centreline velocity will be accelerated correspondingly. It is found that the 90° air tab has made the most pronounced effect, followed by the solid tab case. The last one is the 45° air tab case. Further investigation by using the Schlieren Photography method and velocity contours at successive downstream stations reveal that, when the tab's effect propagates into the primary jet, the potential core of the primary jet is bifurcated into two halves. The jet's velocity contours present a correspondingly kidney shape structure. As a result, a larger mixing region between the primary jet and the surrounding air will be exposed, which can directly enhance the jet's mixing with the surrounding air. However, as the jet develops downstream, e.g. $x/D=18.0$, the kidney shape has almost disappeared and is replaced by an elliptical shape of the

velocity contours, but the mixing region is still larger comparing to the free jet case. To evaluate the overall entrainment enhancement, the jet's mass flux at successive downstream stations is calculated. The tabs have significantly increased the entrainment rate by almost 30%. For the air tab cases, the rates of increase for both cases are nearly the same as the solid tab case (to be within 5%).

The streamwise vortices generated by both solid tab and air tab are also measured. It is the existence of the streamwise vortices that can accelerate the generation of turbulence in the jet so as to increase the mixing between the jet and the surrounding air in small scale. The streamwise vortices in the 90° air tab case shows to be greatest in strength and is located nearest to the jet's centre. This is followed by the 45° air tab case and the solid tab case.

Figure 4.1 Centreline velocity decay for respective cases at subsonic condition $Me = 0.8$, with air injection at $M = 1.0$

Figure 4.2 Centreline velocity decay for different injection for the 90° air tab case

(a) Case 1

(b) Case 2

(c) Case 3

(d) Case 4

Figure 4.3 Schlieren images for respective case at primary jet velocity $M_e = 0.8$, and air injection at $M = 1.0$

(i) Case 1

(ii) Case 2

(iii) Case 3

(iv) Case 4

Figure 4.4a Velocity contours at $x/D=4.0$ for four cases, with contour level 0.1, $Me = 0.8$, and $M = 1.0$

(i) Case 1

(ii) Case 2

(iii) Case 3

(iv) Case 4

Figure 4.4b Velocity contours at $x/D=6.0$ for four cases, with contour level 0.1, $Me = 0.8$, and $M = 1.0$

(i) Case 1

(ii) Case 2

(iii) Case 3

(iv) Case 4

Figure 4.4c Velocity contours at $x/D=10.0$ for four cases, with contour level 0.05, $Me = 0.8$, and $M = 1.0$

(i) Case 1

(ii) Case 2

(iii) Case 3

(iv) Case 4

Figure 4.4d Velocity contours at $x/D=18.0$ for four cases, with contour level 0.05, $Me = 0.8$, and $M = 1.0$

Figure 4.5 Variation of the normalized mass flux with downstream distance at $M_e = 0.8$ and $M = 1.0$ for respective cases

(a) Case 2

(b) Case 3

(c) Case 4

Figure 4.6 Contours of the normalized streamwise vorticity (RHS) and normalized streamwise velocity (LHS) for tabbed cases at cross-sectional plane $x/D=2.0$, with the interval levels at 0.05 and 0.1 respectively

(a) case 2

(b) case 3

Figure 4.7 Schematics for the streamwise vortices generated by the solid tab and 90° air tab

Chapter 5

Experimental results: primary jet flow at supersonic condition ($M_e = 1.3$)

5.1 Introduction

In this chapter, the investigation of the solid tab and air tab's effect on supersonic jet will be presented. The primary jet's velocity is set at $M_e = 1.3$. The air tab applied in the supersonic condition is still maintained at $M = 1.0$. Since the primary jet is operated at supersonic condition, it is necessary to consider the momentum ratio between the primary jet and the air tab's injection, which is

$$M.R. = \frac{\rho_{at} U_{at}^2 d^2}{\rho_e U_e^2 D^2} \quad (5.1).$$

According to the one dimensional isentropic flow assumption,

$$\rho = \rho_t \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{-1}{\gamma - 1}} \quad (5.2),$$

$$U^2 = M^2 \cdot \gamma RT \quad (5.3)$$

and

$$T = T_t \left(1 + \frac{\gamma - 1}{2} M^2\right)^{-1} \quad (5.4).$$

The momentum ratio of the air tab to the primary jet can be written as:

$$M.R. = \frac{\rho_t \left(1 + \frac{\gamma - 1}{2} M_{at}^2\right)^{\frac{-1}{\gamma-1}} \cdot M_{at}^2 \cdot \gamma R \cdot T_t \left(1 + \frac{\gamma - 1}{2} M_{at}^2\right)^{-1} \cdot d^2}{\rho_t \left(1 + \frac{\gamma - 1}{2} M_e^2\right)^{\frac{-1}{\gamma-1}} \cdot M_e^2 \cdot \gamma R \cdot T_t \left(1 + \frac{\gamma - 1}{2} M_e^2\right)^{-1} \cdot D^2} \quad (5.5)$$

In the present work, $M_e=1.3$ and $M_{at}=1.0$ respectively, so that the momentum ratio is at about 0.538%. For the subsonic case ($M_e = 0.8$, $M_{at} = 1.0$), the momentum ratio would be at about 0.781%.

The experimental results and discussion for the four cases will be presented. Meanwhile, the comparison between the supersonic case and subsonic case will be highlighted. In addition, the noise measurement

results will also be presented. That is due to the importance of the screech phenomenon at the supersonic jet flow. The jet's flow structure under the tab's effect in supersonic condition should be more complex comparing to that of the subsonic. Thus more attention will be paid to the flow visualization results.

5.2 Experimental results

5.2.1 Noise spectra of the flow field

This measurement is performed when the supersonic jet is operated at under-expanded condition with the operated stagnation pressure inside the chamber higher than the nozzle designed pressure. With an appropriate convergent-divergent nozzle (CD nozzle) applied together with the used stagnation pressure, the exit Mach number can reach $M_e = 1.63$. For the importance of the screech in supersonic flow, Zaman has stated (1996), *“the screech is a phenomenon that occurs in imperfectly expanded jets due to the interaction of coherent azimuthal vortical structures with the standing shock-expansion cell. The vortical structures are organized and rendered periodic through a feedback loop. The complete mechanism remains unclear, but the interaction also results in the emission of a tone of definite frequency and high intensity”*. Zaman (1996) also analysed the

impact of the screech on the jet's spreading, and found that screech was accompanied by the jet's mixing enhancement. For example, when the external acoustic excitation applied on the jet was set at preferred mode, the azimuthal vortical structure occurring from the nozzle exit would be reorganized and intensified in the near field. As these vortical structures convecting downstream, they would break down into disorganization at the end of the jet's potential core which would be accompanied by an increase in entrainment.

Fig 5.1 shows the sound pressure spectra for each tabbed cases. The free jet case has already been incorporated into every figure for comparison. As shown, both solid tab and air tab have eliminated the screech component and its harmonics presented in the free jet case. Similar result is also observed in Ahuja & Brown (1989). For the free jet case, the smaller peak appearing at about 10 kHz is the fundamental screech component with its corresponding Strouhal number ($St = f \cdot D/U_e$) at about 0.23 based on the jet exit velocity and nozzle diameter. This value is agreeable to Zaman's experimental results (1999). In his experiment, when four tabs were applied to the free jet, the effect of decreasing the screech pressure amplitude would be even more pronounced. The reason why the tabs can

eliminate the screech component of under-expanded supersonic jet is that the occurrence of the screech phenomenon is highly related with the symmetry of the nozzle exit lip. Since inserting tabs interrupts the symmetry of the nozzle exit lip, the screech is consequently eliminated. Another observation has to be mentioned is that there was a shift in the sound pressure level (SPL) from lower frequency to higher frequency for all the three tabbed cases. Referring to the fact that human hearing ranges from 20Hz to 20KHz, if this shift is from audible to ultrasound range, it would be almost as effective as the elimination of the noise. Actually, this observation is made based on the present nozzle exit diameter. When the nozzle increases to the realistic condition, further investigation will be required. During the three tabbed cases, case 3 shows the lowest peak value of SPL, i.e. at around 110dB.

5.2.2 Centreline velocity decay

Fig 5.2 shows the decay of the velocities at jet's centreline with respect to the normalized downstream distance. The measured points are captured in the same way as that for the subsonic case, i.e. from $x/D=0.5$ to $x/D=26$ with the step of $0.5D$.

It is shown in the figure that the free jet maintains its potential core to about $5D$ downstream. The velocity decay rate defined in Chapter 4 for the free jet in the subsequent region is calculated to be at about -0.8 before $x/D=10.0$, which means that the two velocity decay rates for subsonic case and supersonic case are at the same level of magnitude.

Comparing to the results obtained under the subsonic condition, both solid tab and air tab have shown less influence on the jet's centreline velocity decay. The solid tab (case 2) and 45° air tab (case 4) have just reduced the jet's potential core length to be at about $3D$, with their velocity decay rate at -0.09 and -0.10 respectively. The most pronounced one (case 3) achieves the effect that the jet's potential core length is shortened to be at $2D$ followed by the velocity decay rate at -0.16 . The changes of the velocity decay rates for the tabbed cases in supersonic condition are not as deep as that found in the subsonic condition, which can be easily identified from $x/D=8.0$ on.

5.2.3 Flow visualization results

Fig 5.3 shows the flow visualization results for respective cases. In these images, the black circle in the background could vaguely be seen. It is

actually due to the diffraction of the knife edge. However, the intensity of the black circle is so low that it didn't affect the acquisition of the flow pattern. Similar to the images obtained in subsonic flow, the boundaries between the jet and the surrounding air are roughly indicated by the superimposed black lines.

In Fig 5.3(a), the free jet is discharged from the nozzle. A potential core can clearly be seen. The jet's plume is more visible comparing to the subsonic jet (Fig. 4.3(a)), since the supersonic jet has greater density gradient along the longitudinal direction. The mixing between the jet and the surrounding air becomes pronounced since $x/D=5.0$, which is agreeable with the centreline velocity distribution (Fig. 5.2).

There are two side views for each tabbed case. Fig 5.3(b-1), (c-1) and (d-1) show the view when the light beam is perpendicular to the tab's centreline (denoted as view i), while Fig 5.3(b-2), (c-2) and (d-2) show the view when the light beam is parallel to the tab's centreline (denoted as view ii).

Fig 5.3(b-1) and (b-2) show the flow visualization results for the solid tab. In view i (Fig 5.3(b-1)), the structure marked by “x” is highlighted, which isn’t captured in the subsonic regime. The “x” structure should be the oblique shock wave generated by the solid tab. The affirmation of the oblique shock wave could be analysed from the visible brightness difference between the left and right hand side of the “x” structure. This brightness difference is caused by the air density difference according to the Schlieren Photography principle. The air density difference is due to the existence of the shock wave. Meanwhile, it can be seen that the shock waves repeat themselves in the plume of the jet with successive reflections. Past studies reveal that these shock waves make a great contribution to slowing down the flow’s velocity inside the potential core. In view ii (Fig 5.3(b-2)), the primary jet seems to be divided into three regions by the solid tabs. Regions 1 and 3 are less influenced by the solid tab than region 2. The “w” shaped line corresponds to the plane with the same density or the same velocity. The “w” shaped line also demonstrates the existence of the shock wave. Besides, from side view ii, it can be seen that the jet’s mixing enhancement becomes noticeable from about $x/D=3.0$ and the width of the jet is apparently increased comparing to the free jet case.

In Fig 5.3(c-1), the injection for the air tab is tilted at 90° with respect to the primary jet. The primary jet seems to be disturbed ever since it is discharged from the nozzle. The turbulence makes its appearance starting from the nozzle exit plane, which can be seen from the graininess structure's distribution. Although there isn't clear evidence of the shock wave as the solid tab case, the relatively darker area corresponds to the negative density gradient and it should also be considered as the existence of the shock wave. In side view ii of case 3 and Fig 5.3(c-2), the flow pattern is almost the same as that for solid tab case (Fig 5.3(b-2)). Regions 1 and 3 seem to be less influenced by the air tab than region 2, which is the location where the interaction between the injection from the air tab and the primary jet happens. It can be anticipated that the streamwise velocity contours would no longer be circular at the stations where the three regions appear at the same time. Besides, the length of the jet potential core identified from this figure is at about $x/D=2.0$, which is consistent with the result shown in Fig 5.2.

In the side view i of case 4 and Fig 5.3(d-1), a structure "x" is established which is similar to that in Fig 5.3(b-1). And the successive reflection of the shock wave ("x" structure) can also be captured in the

picture. However, comparing to shock wave in Fig 5.3(b-1), this shock wave appears to be “weaker”, which is due to fact that the brightness difference between the two sides of the shock wave is not as sharp as that in the solid tab case. In Fig 5.3(d-2), the flow pattern shown in this figure is similar to that in Fig 5.3(c-2).

5.2.4 Iso-surfaces of normalized velocity

Schlieren images may provide an overall impression of the tab’s effect on the jet’s spreading. The velocity iso-surfaces in jet’s wake would quantitatively indicate the jet’s evolution and help to reveal some details of the flow field.

The measurements are conducted in the same method as the velocity contour measurement in the subsonic condition. The measured planes start from $x/D=2.0$ and end at $x/D=18.0$. Fig. 5.4 shows the velocity iso-surface at $U/U_e=0.1$. For clarification, the velocity contours at the four respective planes have been incorporated into each figure. In Fig 5.4(a), without the disturbance of the tab, the iso-surface for the free jet exhibits a circular cone, as may have been expected. The width of the jet at $x/D=18.0$ reaches about $3.5D$. For case 2 and Fig 5.4(b), the solid tab has made an indentation

into the primary jet. The indentation is seen to persist into the jet's far field so as to compress the jet's wake into an elliptical shape. Actually, this indentation corresponds to region 2 in Schlieren pictures (Fig 5.3(b-2)). The indentation starts from the location of the solid tab and eventually extends to the whole jet. By the time the jet arriving at $x/D=18.0$, the width of the jet has increased to about $4.4D$. For case 3, Fig 5.4(c) shows the same overall trend with the solid case. This indentation is made by the injection of the air tab rather than the solid tab. As it is shown that, the degree of the indentation is not as deep as the solid tab case at $x/D=2.0$. The greater indentation effect at jet's near field for the solid tab case doesn't contribute to the jet width increase in the far field so that the jet width for the 90° air tab case at $x/D=18.0$ is even larger, i.e. $4.9D$. For case 4 and Fig 5.4(d), the indentation at jet's near field at $x/D=2.0$ is the shallowest one. And the jet's width at $x/D=18.0$ is just $4.2D$ which is less than the 90° air tab case by almost 14%.

5.2.5 Mass flux distribution

Using the same method as in the subsonic case, four cross sectional plane are measured for the mass flux distribution, i.e. at $x/D=6.0$, 10.0 , 14.0 and 18.0 respectively. The region where the velocity is lower than 1%

of the local centreline velocity has been truncated. Acceptable repeatability has been obtained.

It is clear that the mass flux has been significantly increased by both the solid tab and the air tab by almost 25% at the initial stage $x/D=2.0$. And the increase made by the tabs keeps getting bigger as the jet spreads downstream. On the other hand, the mass flux data shown in Fig 5.5 is consistent with the velocity iso-surface data shown in Fig 5.4. Case 3 shows the most pronounced effect on the mass flux where the jet's width is $4.9D$ at $x/D=18.0$, while case 4 shows the least influence on the mass flux where the jet's width at $x/D=18.0$ is at about $4.2D$.

It should be noted that, comparing to the free jet's spreading in the subsonic condition, the supersonic jet exhibits a smaller increase in the mass flux. For example, when the jet arrives at $x/D=18.0$, the normalized mass flux $\dot{m}/\dot{m}_e$ for the subsonic jet reaches about 4.5, while it is a little bit more than 3.0 for the supersonic jet. This is believed to be related to the increase of the jet's compressibility. Same phenomenon has been presented by Samimy et al. (1993). On the other hand, under the subsonic condition, three tabbed cases keep little difference between each other in

the mass flux distribution. But in the supersonic regime, the 45° air tab case shows apparently the least effect.

5.3 Summary

To perform a comprehensive comparison between the solid tab and the air tab, further investigation is conducted at the supersonic condition $Me = 1.3$. The experiment results present an overall trend similar to that found in the subsonic condition. However, there are still some discrepancies between the supersonic regime and the subsonic regime.

The sequence of the tab's effect on the jet's centreline velocity decay appears to be the same in both supersonic regime and subsonic regime, i.e. 90° air tab case shows the most prominent effect, followed by the solid tab case, the 45° air tab case shows to be minimum. But the effect of the tabs on the subsonic primary jet is more pronounced than that on the supersonic primary jet.

The images from Schlieren Photography show that the tabs introduce shock waves inside the supersonic jet's potential core. And the existence of the shock waves helps to shorten the jet's potential core length, which is

not captured under the subsonic condition. The velocity iso-surface results reveal that both the solid tab and the air tab can make an indentation into the plume of the primary jet and this indentation seems to be able to persist into the jet's far field so as to compress the jet's wake into an elliptical shape. The jet's width for the 90° air tab case shows to be $4.9D$ at $x/D=18.0$, followed by the solid tab case at $4.4D$ and the 45° air tab case at $4.2D$.

The mass flux increase in the supersonic condition for respective cases presents the same sequence as that for centreline velocity decay. However, the mass flux enhancement effect in the supersonic condition shows to be less pronounced than that in the subsonic condition, which is believed to be related to the supersonic jet's higher compressibility comparing to the subsonic jet.

Screech is an important characteristic in the supersonic jet flow. The measurement of the jet's far-field sound pressure spectra is also performed. The obtained figures indicate that both solid tab and air tab have eliminated the screech and its harmonics presented in the free jet case. And there is a shift in the sound pressure level (SPL) from lower frequency to higher frequency for the tabbed cases comparing to the free jet, which is actually

from audible to ultrasound range for human hearing. During the three tabbed cases, case 3 shows the lowest peak value of SPL.

(a) Case 2

(b) Case 3

(c) Case 4

Figure 5.1 Far-field sound pressure spectra for the under-expanded jet for respective cases

Figure 5.2 Centreline velocity decay for respective cases at supersonic condition $M_e = 1.3$, and $M = 1.0$

(a) Case 1

(b-1) Case 2

(b-2) Case 2

(c-1) Case 3

(c-2) Case 3

(d-1) Case 4

(d-2) Case 4

Figure 5.3 Schlieren images for respective case at primary jet velocity $Me = 1.3$, and $M = 1.0$

(a) Case 1

(b) Case 2

(c) Case 3

(d) Case 4

Figure 5.4 Iso-surfaces of the normalized velocity at $Me = 1.3$, $U/U_e = 0.1$; velocity contours with level at 0.1, for respective cases

Figure 5.5 Variation of the normalized mass flux with downstream distance at $M_e = 1.3$ and $M = 1.0$ for respective cases

Chapter 6

Numerical simulation for the solid tab case and the 90° air tab case

6.1 Introduction

The experimental investigations on the solid tab and the air tab have been conducted. It is noted that some measurements couldn't be performed in the experiments due to the limitation of instruments. In particular, the evolution of the streamwise vortices was difficult to quantify by the five-hole probe, but it may be possible to investigate by numerical simulation.

According to the experimental results, the 90° air tab case is shown to be better than the 45° air tab case in enhancing the jet's mixing. The comparison of numerical simulation results will therefore be conducted on the solid tab case and the 90° air tab case.

In the following sections of this chapter, the computational domain's specifications together with its boundary conditions will first be presented.

The governing equations and turbulence model will be specified subsequently together with the mesh generation method. The computational results will then be presented, including a detailed comparison with the experimental results. This chapter ends with brief concluding remarks.

6.2 Numerical modelling

6.2.1 Domain specification and boundary conditions

The schematics for respective cases under numerical investigation are shown in Fig. 6.1. The computational domain and its corresponding boundary conditions are shown in Fig. 6.2. The primary jet is discharged through a straight pipe with length of 60mm. Due to symmetry, only one quarter of the physical domain is modelled for the present investigation (Steffen et al. (1997) and Berg et al. (2006)). The nozzle diameter is at $D=12.7\text{mm}$, the radius of the domain is set at about $10D$, and the length is set at about $24D$. This can ensure enough space for the spreading of the jet and make the influence by the artificial boundary be kept to a minimum.

In Fig. 6.2, the plane bounded by $y=0$ and $z=0$ is defined as the symmetry plane. The inflow boundary is modelled as fixed total pressure

which can be specified according to isentropic assumption. It should be noted that the boundary layers of the inflow at the nozzle wall, determined from the experimental results (Yu et al. (2008) and Wan & Yu (2011)), are incorporated into the inflow total pressure profile. The outflow boundary is set at fixed static pressure. No-slip condition is specified at the nozzle wall and the annular plane. The cylindrical entrainment boundary is modelled as non-reflection boundary condition, which is the pressure far field condition (Thomas & Salas (1986) and Schulze (1995)).

6.2.2 Governing equations

The jet flow in the present investigation is considered to be steady, three dimensional, turbulent, and compressible. The density is defined by the ideal gas equation. The dynamic viscosity is computed by using the Surtherland law ($\mu = \mu_0 \frac{T_0+T}{T+C} \left(\frac{T}{T_0}\right)^{3/2}$, μ_0 is the reference viscosity, assumed to be 1.7894e-05Kg/(m·s); T_0 is the reference temperature, being 273K; C is the Surtherland constant, at 110K), and the gravity effect can be neglected. Based on the above conditions, the conservation equations, together with the ideal gas equation, can be expressed as:

Momentum equation:

$$\rho \left(u_j \frac{\partial u_i}{\partial x_j} \right) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left(\mu \frac{\partial u_i}{\partial x_j} - \overline{\rho u'_i u'_j} \right) \quad (6.1)$$

Continuity equation:

$$\frac{\partial(\rho u_i)}{\partial x_i} = 0 \quad (6.2)$$

Ideal gas equation:

$$P = \rho RT \quad (6.3).$$

6.2.3 Turbulence model

One equation eddy-viscosity turbulence model, developed by Spalart & Allmaras (1992), has been used in the present computation. The application the S-A turbulence model can be referred to the work of Reddy & Zaman (2006) and Reddy et al. (1999). It has to be noted that, the chosen of the S-A model, rather than $k - \varepsilon$ two equations model, is based on the fact that the $k - \varepsilon$ model would usually over-predict the evolution of the jet (Pope (1978)).

In S-A turbulence model, the relationship between the Reynolds stress in Eq. (6.1) and eddy viscosity can be expressed as:

$$\overline{\rho u'_i u'_j} = -\mu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \quad (6.4)$$

where μ_t is the eddy viscosity. It can be computed using the following equation:

$$\rho u_i \frac{\partial \mu_t}{\partial x_i} = \frac{1}{\sigma_{\mu_t}} \left[\frac{\partial}{\partial x_j} \left\{ (\mu + \rho \mu_t) \frac{\partial \mu_t}{\partial x_j} \right\} + C_b \rho \left(\frac{\partial \mu_t}{\partial x_j} \right)^2 \right] + P_{\mu_t} \quad (6.5)$$

where P_{μ_t} is the production term of the turbulent viscosity. The values of constants used in Eq. 6.5 are $\sigma_{\mu_t} = \frac{2}{3}$, $C_b = 0.622$.

6.2.4 Computational mesh

Multi-block, structured, generalized curvilinear meshes are created for the free jet's computational domain by the use of Gambit software as shown Fig. 6.3. Uniform spacing between the nodes is set inside the nozzle at the cross section plane. Meanwhile, the grids near the nozzle wall have been refined by using the boundary layer setting function. For the flow

field outside the nozzle, the meshes are clustered towards the jet flow's upstream. An expanding grid with the expansion factor 1.05 in y and z directions is used. In streamwise or x direction, the initial spacing of the nodes is set to be 0.3 with the interval count to be 120 in the whole jet's downstream field. For the solid tab case, to avoid the topology complexity caused by the tab, unstructured grids are generated in the block containing the tab. The structured grids are also generated in other blocks of the computation domain.

Mesh independence study has been conducted with the following node distributions in x, y and z direction, i.e. $60 \times 48 \times 48$ (coarse), $120 \times 78 \times 78$ (medium), $120 \times 88 \times 88$ (fine). The differences in the centreline velocity decay between the second grid case and the other two grid cases are all within 3%. As a result, the medium grid distribution has been chosen for further investigation.

The numerical computation are conducted by the finite volume method developed by Patankar (1980) via the commercial CFD code (Fluent, v6.3.26). The conservation equations for momentum and pressure-based continuity are solved together by the coupled algorithm based on the work

of Rhie & Chow (1983). The coupled discretized mass and momentum equations, the energy equation and the turbulence equation are iterated by the use of AMG (algebraic multi-grid) acceleration.

6.3 Results and discussion

6.3.1 Comparison of the jet's centreline velocity

Fig. 6.4 shows the jet's centreline velocity decay by experimental and numerical methods for three cases in both subsonic $M_e = 0.8$ and supersonic $M_e = 1.3$ conditions. All the presented velocity data have been normalized by the velocity at the nozzle exit (U_e).

For the free jet case and Fig. 6.4(a), it is shown that the simulated results agree with the experimental results pretty well for the two conditions.

For the solid tab case and Fig. 6.4(b-i), when the jet is discharged under subsonic condition, the experimental results show an initial acceleration of the centreline velocity which is believed to be due to the vena contracta effect. This will usually happen when the jet flow is discharged from a noncircular orifice. In the actual experiment, the distance between the nozzle exit to the location where the highest velocity appears to be rather

short, at about $0.16D$, and measurement becomes difficult due to the probe's interference to the flow field. Nevertheless, the agreement between the experiment and simulation data is generally good. Under the supersonic condition and Fig. 6.4(b-ii), the shock-expansion wave caused by the solid tab has become more visible in the computational result. Careful examination of the shock-expansion wave shows that the distance between a normal shock and the next one is at about $0.4D$, and the pressure gradient existing here is believed to be too large for the pressure probe to distinguish the difference between the two adjacent measuring grids. That may be the reason why the shock-expansion wave is not present in the centreline velocity decay by the measurement. However, the existence of the shock-expansion wave is clearly captured by the Schlieren images (Fig. 5.3), which also indicates the agreement between the experimental results and computational results. The overall trend of the centreline velocity variation in supersonic condition is almost the same as that in subsonic condition, including the length of the jet's potential core, the appearance of the inflection point in the velocity decay region and the velocity decay rate. The comparison clearly suggests that the effect of the solid tab on the primary jet is independent of the compressibility of the primary jet (Samimy et al. (1993)).

For the 90° air tab case and Fig. 6.4(c-i), when the primary jet is at the subsonic condition, the centreline velocity obtained by simulation shows an even greater initial acceleration comparing to the solid tab case. The subsequent velocity decay follows almost immediately without the appearance of the jet's potential core. This suggests that the penetration effect caused by the 90° air tab should be greater than that caused by the solid tab. Under the supersonic condition and Fig. 4(c-ii), the shock-expansion wave caused by the injection from the air tab can be clearly captured by simulation. The wave's magnitude seems to be relatively stronger than that caused by the solid tab, which can be identified by the velocity fluctuations in Fig. 6.4(b-ii) and Fig. 6.4(c-ii).

6.3.2 Comparison of the jet's streamwise velocity contours at certain cross-sectional plane

The detailed comparisons between the experimental and computational axial velocities (U/U_e) for the three cases are shown in Fig. 6.5. The contour plots are presented in such way that the experimental and its corresponding computational results are arranged to have the same contour levels. For the subsonic condition, the cross sectional plane is located at $x/D=2.0$, while for the supersonic condition, the plane is at $x/D=4.0$. This

arrangement is decided based on the limitation of the experimental instrument and flow details in the near field. The outline for the nozzle exit has been incorporated into each figure, together with the projected location of the tabs.

For the free jet case and Fig. 6.5(a), the agreement for the size of the jet's potential core and the shape of velocity contour is excellent between experiment and simulation for both subsonic and supersonic conditions. For the solid tab case and Fig. 6.5(b), for the subsonic cases, contours for both velocities show a kidney shape structure. The jet's potential core size and the later expansion of the jet for the two results match each other very well. For the supersonic cases, since the location is chosen at $x/D=4.0$ which is farther away than the location at $x/D=2.0$, the jet's potential core is seen to bifurcate into two parts. For the 90° air tab case and Fig. 6.5(c), it is observed that the computed velocity contours has a slightly larger spread in the lateral direction (y direction) especially in supersonic condition, which is believed to be due to the excess diffusion of the S-A turbulence model (Reddy & Zaman (2006)).

6.3.3 Comparison of the streamwise vorticity

The comparison of the streamwise vortices is presented in Fig. 6.6. Due to the measurement range of the five-hole probe, the measurement of the streamwise vortices would only be performed in the subsonic condition. Hence the comparison can only be conducted in the subsonic case. The cross-sectional plane chosen for comparison is located at $x/D=2.0$. And the magnitude of the streamwise vorticity has been normalized by U_e/D . For the solid tab case and Fig. 6.6(a), the cores for the two vortices are located at around the outline of the nozzle exit. Comparing to the experimental result, computed vortices appear to occupy slightly larger area. On the other hand, the highest magnitude for the experimental vortex is at 0.4; while it is at 0.6 for the computed vortex. Considering the spatial resolution, measurement sensitivity and the derivation errors from the experiment, these two values are basically agreeable with each other.

For the 90° air tab case and Fig. 6.6(b), the cores for the vortices appear inside of the nozzle exit's outline, i.e. the penetration into the jet's plume made by the 90° air tab is deeper than that made by the solid tab.

Meanwhile, the peak magnitude and the location of the vortex match each other very well.

6.3.4 Discussion on the evolution of the streamwise vortex in subsonic primary jet

The above comparison demonstrates the fact that simulation is feasible to predict the jet's feature reasonably well. Therefore, in this section, using the computed results, the evolution of the streamwise vortices will be discussed further. The existence of the streamwise vortex is largely responsible for the reduction of the jet's potential core length (see Fig. 6.4) and the distortion of the velocity contours at the cross-sectional plane (see Fig. 6.5). Further investigation of the streamwise vortex can reveal the details of the jet's structure. Since the compressibility of the primary jet is not essential in generating the streamwise vortices (Zaman et al. (1994)), the investigation of the evolution of the streamwise vortices will only be performed in the subsonic condition, i.e. $M_e = 0.8$.

Fig. 6.7 and Fig. 6.8 show the development of the normalized streamwise vortices at successive downstream cross-sectional planes, i.e. $x/D=1.0, 2.0, 3.0$ and 4.0 , for the solid tab case and at the same planes for

the 90° air tab case respectively. The lowest contour level is kept at 0.1, which is about 5% of the peak streamwise vorticity. This level can help us to identify the variation of the shape of the streamwise vortex contours. The sequential plotting of the streamwise vortex provides an impression that, as the plane moves further away from the nozzle exit, the magnitude of the streamwise vortices decays continuously. Beyond $x/D=4.0$, the streamwise vortices will reduce to a negligible level.

For the solid tab case and Fig. 6.7, it presents the same result shown in Fig. 6.6 so that the description of the streamwise vortices is neglected here. However, it has to be mentioned that, for the 90° air tab case and Fig. 6.8, the main part, or the centre part, of the streamwise vortices is formed by the air injection from the air tab. Besides, a “mushroom” structure is being established apparently above the centre of the streamwise vortices. Actually this “mushroom” structure is originated from the primary jet which wraps around into the rear side of the air injection as in the situation of a solid cylinder’s wake. As the jet spreads downstream, the “mushroom” is gradually merging into the streamwise vortices. When the jet arrives at $x/D=4.0$ and Fig. 6.8(d), the “mushroom” becomes undistinguishable from the streamwise vortices.

The peak value for the streamwise vortices at respective downstream stations presented in Fig. 6.7 and Fig. 6.8 has been extracted and plotted in Fig. 6.9. It is clear that, for both the solid tab case and the 90° air tab case, the decay of the streamwise vortices from $x/D=1.0$ to $x/D=4.0$ is rapid. At $x/D=1.0$, the streamwise vortex for 90° air tab case has its higher magnitude than that for the solid tab case by almost 50%, which is believed to be due to the vortices generation mechanism and will be discussed in next section. However, when the jet reaches $x/D=4.0$, the difference between them becomes negligible. On the other hand, the spacing between the counter-rotating streamwise vortices has also been plotted in Fig. 6.10. It can be observed that the streamwise vortices generated by the 90° air tab case locate closer to each other initially. As the jet propagates downstream, the streamwise vortices for the 90° air tab separates faster than that for the solid tab. That is because the air injection for the air tab case can penetrate deeper into the primary jet due to its high initial momentum. However, after the injected air moves further away from the exit, it is pushed out by the primary jet gradually due to the diminishing momentum. When the jet arrives at $x/D=4.0$, the spacing between the two vortices for the 90° air tab case is even larger than that for the solid tab case.

6.3.5 Discussion on the generation mechanism for the streamwise vortices by streamlines

The generation mechanism for the streamwise vortices by the solid tab has already been discussed by Zaman et al. (1994). With the reference to the streamlines, it may be more visible to compare the generation of the streamwise vortices between solid tab and the air tab.

As shown in Fig. 6.11, on each side of the tab, five different streamlines have been plotted. Line 5 is the one closest to the nozzle wall, and line 1 is sequentially the farthest one to the nozzle wall. When the air flow approaches the solid tab, the flow will be guided to move towards the lateral direction (y direction), but it will not wrap around immediately into the rear side of the solid tab. It means that the streamwise vortices are not formed immediately behind the solid tab, although the velocity gradients or pressure gradients for the production of the streamwise vortices have already existed. After the flow passes the position indicated by the arrow at about $0.5D$, streamline 5 starts to turn into the negative y direction and thus the streamlines 1 to 5 begin to form into a spiral structure, i.e. the streamwise vortices are beginning to form. The cross-sectional plane (A-A) in Fig. 6.11 has been extracted out and

presented in Fig. 6.12. In Fig. 6.12(a), the streamlines 1 and 5 around the solid tab have been plotted and the solid tab outline has been incorporated into the figure. The vortex generation mechanism proposed by Zaman et al. (1994) are confirmed here.

Since the description about the two sources responsible for the generation of the streamwise vortices has been presented in Chapter 2, it will only be briefly summarized here. Due to the fact that the streamlines coming from the primary jet are forced to turn into y direction, there must be an existence of the pressure gradient in y direction which is plotted schematically in Fig. 6.12(b). The pressure gradient in the y direction, together with the presence of the wall, will enable the air flow to change direction forming part of the streamwise vortices. The above pressure gradient is what Zaman et al. (1994) referred to as source I.

Source II is sketched in Fig. 6.12(c). Sheets of vorticity are shedding from the right side of the delta tab, which is formed by the pressure difference between the tab's upstream face and downstream face. The vorticity is initially aligned with the side of the delta tab. As it develops downstream, it will be reoriented by the velocity gradient ($\partial U/\partial y$ and

$\partial U / \partial z$) in the shear layer to become streamwise. Although the existence of source II can not be easily identified from the streamlines in Fig. 6.11, it is the existence of source II that makes the streamline 5 to turn into the negative y direction in the relatively far field and to form the spiral structure.

For the 90° air tab case and Fig. 6.13, it is shown that the air injection is firstly bended into streamwise direction by the primary jet. At the same time, the primary jet travels from the upstream surface of the air injection into the downstream surface so as to twist the air injection into a spiral structure. When the primary jet wraps around the air injection from the left and right sides, coupled with the decay of the air injection's momentum, the plume of the air injection will be bifurcated into two parts. Each part corresponds to a half of the pair of counter-rotating streamwise vortices. The cross-sectional plane (A-A) has also been extracted out and presented in Fig. 6.14. The air injection is expected to behave as a virtual cylinder which is indicated by the shadowed rectangular region in Fig. 6.14(a). Similar to the solid tab case, the two sources for the generation of the streamwise vorticity in the air tab case can also be identified (see Fig. 6.14(b) and Fig. 6.14(c)).

Source I is also the upstream pressure hill (seeing Fig. 6.14(b)), which is formed by the virtual cylinder's blockage to the primary jet. The pressure hill, caused by the blockage effect, works together with the nozzle wall to generate the streamwise vortices. The generation process by source I is the same as that for the solid tab. For source II and Fig. 6.14(c), it is basically the same as source II for the solid tab. However, it has to be mentioned that, as the vortex formed at the sides of the air injection, the air injection from the air tab is also induced to twist into the spiral structure. Furthermore, combining the results presented in Fig. 6.8, it is observed that major part of the streamwise vortices in the air tab case originates from the air injection itself. The air flow from the primary jet may just contribute a little part of the streamwise vortices. That is the difference with the solid tab, and may also be the reason why the magnitude of the streamwise vortices is greater than that for the solid tab.

6.4 Summary

In this chapter, the comparison between the experimental and computational results has been presented for both subsonic and supersonic conditions. The overall computed jet's mixing enhancement effect is shown to agree well with the experimental results.

The centreline velocity decays generated by the numerical method agree with the experimental results very well in both near field and far field for the three cases. The comparison of the streamwise velocity contours reveals that the experimental results and computational results match in the scope of the jet's spreading and the occupying region of the potential core. The comparison of the streamwise vortices is presented. The streamwise vortices generated by the solid tab in computational method appear to be larger and higher than that in the experimental method. It is possible that the measurement of the vorticity by using the five-hole probe has its limitation in the spatial resolution and derivation accuracy.

Besides of the comparison between the computational results and the experimental results, the analysis on the evolution of the streamwise vortices is conducted when the primary jet is in subsonic condition. The results reveal that the 90° air tab could generated stronger streamwise vortices initially comparing to the solid tab. However, as the jet develops downstream, the streamwise vortices for the 90° air tab case would also decay faster than that for the solid tab case. When the jet arrives at $x/D=4.0$, the difference between the two cases becomes negligible.

The vortex generation mechanism for both the solid tab and the air tab has been investigated by examining the streamlines around the tabs. For the solid tab case, the two sources responsible for the production of the streamwise vortices proposed by Zaman et al. (1994) are confirmed here. It is noted that the streamwise vortices are not formed immediately after the tab, but rather formed from about $0.5D$ onwards. For the 90° air tab case, the two generation sources being the same with the solid tab case are presented. The major difference is that, for source II, the injected air column is being twisted and forms the main part of the streamwise vortices. The air flow discharged from the primary jet twines itself around the injected air column and finally merges to become the streamwise vortices. However, it only contributes a little part of the streamwise vortices.

(a) Free jet (case 1)

(b) Solid tab (case 2)

(c) 90° air tab (case 3)

Figure 6.1 Tab configurations under investigation

Figure 6.2 Computational domain and its boundary condition

Figure 6.3 Computational mesh for the domain

(a) free jet

(i) $Me=0.8$

(ii) $Me=1.3$

(b) solid tab

(i) $Me=0.8$

(ii) $Me=1.3$

(c) 90° air tab

(i) $Me=0.8$

(ii) $Me=1.3$

Figure 6.4 Comparison of the centreline velocity decay for the three cases in both subsonic $Me = 0.8$ and supersonic condition $Me = 1.3$

(a) free jet

(b) solid tab

(c) 90° air tab

Figure 6.5 Comparison of the axial velocity contours for three cases, at $x/D=2.0$ for subsonic condition and at $x/D=4.0$ for supersonic condition, with contour level at 0.05

(a) solid tab

(b) 90° air tab

Figure 6.6 Comparison of the streamwise vorticity contours for the two tabbed cases at subsonic condition and at cross-sectional plane $x/D=2.0$

Figure 6.7 Contours of the streamwise vorticity at successive downstream stations for the solid tab case at subsonic condition $M_e = 0.8$

Figure 6.8 Contours of the streamwise vorticity at successive downstream stations for the 90° air tab case at subsonic condition $M_e = 0.8$

Figure 6.9 Variation of the peak streamwise vorticity for the two tabbed cases

Figure 6.10 Variation of the spacing between the counter-rotating streamwise vortices for the two tabbed cases

Figure 6.11 The streamlines of the air flow around the solid tab at subsonic condition

Figure 6.12 Schematics of the vortex generation mechanism for the solid tab case (after Zaman et al. 1994)

Figure 6.13 The streamlines of the air flow around the 90° air tab at subsonic condition

Figure 6.14 Schematics of the vortex generation mechanism for the 90° air tab case

Chapter 7

Conclusions and recommendations

7.1 Conclusions

Mixing enhancement of jet flow is an important topic in the area of fluid dynamics. The solid tab technique, as an effective passive approach, has long been investigated. However, it will introduce thrust loss due to blockage effect to the nozzle exit. An alternative technique, namely the “air tab”, is introduced in the present investigation. It is achieved by injecting a small amount of air into the primary jet to take the place of the solid tab. The advantage of this air tab technique is that it can function as effectively as the solid tab to enhance the jet’s mixing but it will not introduce any thrust loss. Two configurations of the air tab, i.e. 45° air tab and 90° air tab, have been considered. The comparison of the jet’s mixing enhancement between the solid tab and the air tab is firstly conducted via experiments. The experiments are performed at primary jet velocity in subsonic ($M_e = 0.8$) and supersonic ($M_e = 1.3$) conditions respectively. Several mixing indicators, including the centerline velocity decay, the Schlieren flow images, the axial velocity contours, the streamwise

vorticity contours and the mass flux variation, are discussed. Numerical simulations of the solid tab and the air tab have also been performed. The simulated results are used to analyze the generation and evolution of the streamwise vortices. The following remarks can be summarized based on the above work.

1. When the primary jet is operated at subsonic regime ($M_e = 0.8$), the application of the tabs can promote reducing the length of the jet's potential core by at least 50%, and a faster velocity decay thereafter. Among the three tabbed cases, 90° air tab presents to be the most pronounced one, followed by the solid tab and the 45° air tab. However, when the primary jet velocity is changed to supersonic regime ($M_e = 1.3$), the centerline velocity decay's acceleration effect made by the tabs is not as significant as that in subsonic regime, which is believed to due to the higher compressibility of the supersonic jet.

2. The sound pressure spectra of the supersonic jet ($M_e = 1.63$) at far field has been measured. The results indicate that both solid tab and air tab can eliminate the screech and its harmonics existed in the free jet case. There is a shift in the sound pressure level (SPL) from lower frequency to

higher frequency for the tabbed cases comparing to the free jet, which is actually from audible to ultrasound range for human hearing. Among the three tabbed cases, 90° air tab case shows the lowest peak value of SPL.

3. The Schlieren photography results in both subsonic condition and supersonic condition reveal that the tabs can make their indentation into the jet's wake, which is easily identified from the existence of the jagged edges in between the jet's plume and the ambient air. The mixing region is also enlarged with the effect of tabs. In the supersonic condition, it is worth mentioning that both the solid tab and the air tab introduce the shock waves inside the jet plume which can help to shorten the length of the jet's potential core.

4. The streamwise velocity contours at successive cross-sectional planes and the velocity iso-surface of the jet's wake reveal that, the tabs can make their indentation into the primary jet so that the jet's plume is bifurcated into a kidney structure with two parts locating symmetrically with the tab's centerline. As the jet spreading downstream, the kidney shape will evolve into an elliptical shape due to the disappearance of the streamwise vorticity and the viscous diffusion. Thus, the width at the jet's

far field can serve as an indication to identify the mixing enhancement degree caused by the tabs. For the subsonic condition, little difference existed between the three tabbed cases. For the supersonic condition, 90° air tab case establishes the largest width, i.e. $4.9D$, at $x/D=18.0$. The solid tab case has about $4.4D$, while the 45° air tab has about $4.2D$.

5. Mass flux distribution with respect to the downstream distance provides the information about the jet's overall entrainment with the surrounding air. The results in subsonic condition reveal that the three tabs can significantly increase the jet's mass flux by almost 30% at $x/D=4.0$, and this increase is almost being kept at constant from near field ($x/D=4.0$) to far field ($x/D=18.0$). The difference between the three tabbed cases is so small that it is within 5%. For the supersonic condition, mass flux increase from the near field ($x/D=4.0$) to far field ($x/D=18.0$) is not as significant as that in the subsonic condition for all the four cases, which is believed to be due to the increase of the jet's compressibility effect. But in the supersonic condition, the difference of the mass flux enhancement among the three tabbed cases shows to be more visible. 90° air tab appears to be the most pronounced one; followed by the solid tab. 45° air tab presents the least effect.

6. When the primary jet is operated at subsonic condition, the streamwise vortices generated by the solid tab and air tab at cross-sectional plane $x/D=2.0$ is measured. The results show that each tab can produce a pair of counter-rotating streamwise vortices distributed symmetrically. The streamwise vortices generated by the 90° air tab shows to be the greatest in magnitude and located nearest to the jet's centre. This is followed by the 45° air tab and the solid tab. The reason for the above observation lay in the streamwise vortices generation mechanism. The mechanism for the air tab case is firstly described as: the primary jet would decelerate near the upstream surface of the air tab injection so as to construct a positive pressure region. The pressure difference between the upstream surface and downstream surface of the air injection would cause a lateral deflection of the primary jet flow, which would gradually change the cross section of the injected stream from circle to a kidney shape as the momentum of the injected air reducing.

7. The comparison between the computational results and experimental results reveals an overall agreement in the three indicators of the flow field, i.e. the jet's centerline velocity decays, the streamwise velocity

contours and the streamwise vorticity distributions. Besides the comparison, the analysis of the evolution of the streamwise vortices reveals that the 90° air tab can generate stronger streamwise vortices at the initial period ($x/D=1.0$) comparing to the solid tab. However, as the jet develops downstream, the streamwise vortices for the 90° air tab case also decays faster than that for the solid tab case. When the jet arrives at $x/D=4.0$, the difference between them becomes negligible.

At the same time, the vortex generation mechanism for both the solid tab and the air tab has been investigated by plotting the streamlines around the tabs. For the solid tab case, the two sources responsible for the production of the streamwise vortices proposed by Zaman et al. (1994) are confirmed here. Meanwhile it is found that the streamwise vortices are not formed immediately after the tab, but rather formed from about $0.5D$ onwards. For the 90° air tab case, the two sources are the same with the solid tab case. The difference is, with the existing of source II, the air injection is being twisted and thus forms the main part of the streamwise vortices. The air flow coming from the primary jet only contributes a little part of the streamwise vortices.

7.2 Recommendations

1. As it is known, the small scale structure is important for investigating the jet's flow field. The small scale structure can help to identify the interaction between the spanwise vortices and streamwise vortices and find the location where the most mixing phenomenon happens. However, it is not feasible to conduct the measurement of the small scale structure due to the limitation of current instrument. Therefore, it may be possible to investigate the small scale feature of the jet's flow further by numerical method.

2. The air tab technique can be investigated by some parametric studies. For example, the continuous air supply for the air tab can be changed to impulse air supply, the orifice of the exit for the air tab can be changed from circular to non-circular, the air tab can also be combined with other mixing device (e.g. acoustic excitation, an elliptical nozzle).

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