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Technical Notes

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Mixing Enhancement in Subsonic Jet Flow Using the Air-Tab Technique

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Nomenclature

A	=	Cross-sectional area
D	=	nozzle exit diameter
F	=	force
K	=	coefficient
M	=	Mach number at nozzle exit
$\dot{m}$	=	mass flux
P	=	static pressure
T	=	thrust
U, V, W	=	corresponding velocity components in x, y and z direction
x, y, z	=	coordinate system adopted
θ	=	angle between the air-tab injection plane and the nozzle exit plane
ρ	=	density

Subscripts

a	=	ambient
at	=	air tab
e	=	nozzle exit
gas	=	exhaust gas force
net	=	net force
p	=	reacting force
tab	=	tabbed case

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I. Introduction

Mixing enhancement in jet flow has long been the topic of extensive research due to its important applications in aircraft propulsion and combustion. It also has military importance when mixing enhancement is used to suppress the infrared red signature for the fighter jet exhausts. Many passive or active approaches or techniques to enhance jet mixing have been developed and explored, and some of these techniques had also been reviewed and summarized by Gutmark and Grinstein [1]. In passive control strategies, the tabs or vortex generators in particular are simple but effective techniques in flow control. Bradbury and Khadem [2] were the pioneers to study the effect of solid tabs on jet flow. They found that the nozzle boundary-layer thickness, turbulence level, and convergent ratio did not have very strong influence on the jet development. On the other hand, to insert small rectangular tabs into the jet flow on the nozzle perimeter would induce some profound effects on the jet development. Since then, many researchers have been working on this technique. Notable examples include Samimy et al. [3], Reeder and Samimy [4], Zaman et al. [5], Yu and Koh [6], Paoli et al. [7] and many others. Zaman [8] conducted a systematic test on a series of nozzles with various shapes or orifices 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 is also found to be significant. The thrust lost due to the tabs varies from 4.1 to 23.7% when the flow blockage (proportional to the facing area of tabs) increases from 1.1 to 14.1%. To minimize the thrust lost caused by tabs but yet maintain its effectiveness in mixing enhancement is important to practical applications. Researchers have been searching for new techniques with better effects on mixing but minimum penalty on thrust. This Note presents results using the so-called air-tab technique. The air-tab technique is achieved by injecting a small amount of air (less than 1% of the volume flow rate of the primary jet) into the plume of the primary jet at choked speed and at certain attacking angles (45 and 90 deg with respect to the primary jet direction). The air-tab technique shows minimum or no impact on thrust, but it would be able to provide significant effect as the solid tab on the mixing enhancement. A similar idea had been used in air and fuel mixing: for example, the experiments conducted by Milanovic and Zaman [9,10]. The description of the experimental setup is presented subsequently. It will be followed by the results and discussion. The Note ends with brief concluding remarks.

II. Experimental Setup and Flow Configurations

A. Compressed Air and Helium Gas Supply and Control System

Experiments were performed at the Fluid Dynamics Laboratory of Temasek Laboratories at the National University of Singapore. Pressured gas required by the experiment was drawn from a compressed-air reservoir made up of 32 commercially available pressurized gas cylinders. During operation, the compressed air from the cylinders passes through a series of ball valves, regulators, and a needle valve before reaching the plenum chamber. The needle valve allows precise adjustment of the pressure inside the plenum chamber. The plenum chamber is lined with a series of honeycomb, perforated plates, and fine screens to reduce the turbulence of the flow before the air exits the plenum chamber into the ambient via the nozzle exit.

To ensure that the flow was consistent during operation, the stagnation pressure inside the plenum chamber was maintained at

$\pm 1\%$ of the theoretical stagnation pressure based on the one-dimensional isentropic flow assumption and maintaining the ambient pressure at 14.696 psig (1.013 bar). A converging nozzle with an area ratio $(A/A^*)9$ had been used. The nozzle had an exit diameter of $\frac{1}{2}$ in. (12.7 mm).

B. Pressure Measurement

A five-tube pitot rake mounted on a 3-axis traverse gear was used to acquire pressure data in the jet's downstream. The pitot tubes were mounted 12.3 mm apart and each has an opening of 1 mm. The overall sampling area is 60×60 mm in the y–z plane for the near-field measurement and 120×120 mm for the far-field measurement. The traverse has a resolution of 1 mm in the streamwise (x direction) and 0.01 mm in the y and z directions. A total of 4 planes (at $x/D = 4$, 6, 10, and 18) were surveyed for each configuration, including the reference case in which no air injection was applied.

C. Flow Configuration

Figure 1 shows schematics of the four cases considered. Case 1 represents the baseline jet. Case 2 had two solid tabs attached to the exit plane of the nozzle and they are 180 deg apart. Each tab was mounted at a 135 deg angle and with a delta tab shape similar to those recommended by Zaman et al. [5]. Each tab had a projected area corresponding to 0.8% of the exit area of the primary nozzle. For the comparability of the air tab and solid tab, the tab base dimension was arranged to be almost the same as the injector diameter for cases 3 and 4. Case 3 had the injectors arranged in such a manner that they were blowing at 90 deg with respect to the direction of the primary jet. The injectors in case 4 were tilted at 45 deg with respect to the primary jet direction.

III. Results and Discussion

A. Centerline Mach Number Distribution

Figure 2 shows the variations of the centerline Mach number with the normalized distance x/D for the respective cases. It can be seen that the potential core for the baseline jet was extended to about 5 diameters downstream of the jet exit plane. It was immediately followed by a fast decay region due to the rolled up of the large-scale Kelvin–Hemholtz type of vortices. The solid-tab case (case 2) and the 45 deg injection case (case 4) had reduced the extent of the potential core region to less than $2D$. The 90 deg injection case (case 3) showed the shortest potential core region (i.e., at about $1D$). It should be noted that the subsequent decay rate after the potential core region was also found to be the highest for the 90 deg injection case. The decay rates for the solid-tab case and the 45 deg injection case are almost the same. The reason for the highest decay rate of 90 deg injection could be due to the fact that the two injections impinge on each other to produce some kind of blockage effect against the primary jet.

B. Mass Flux Distribution

Figure 3 shows the mass flux variation with downstream distance for the respective cases. As shown, the rate of increase for the baseline jet varied almost linearly with downstream distance. The tabs had significantly increased the entrainment rate by almost 30%, as demonstrated by the slopes of the two lines. For cases 3 and 4, the rates of increase for both cases were nearly the same as the solid-tab case (to within 5%).

For the air-tabbed case and as the flow was discharging out from the smaller tube, the momentum of the jet enabled it to penetrate into the primary jet effectively, acting as a solid blockage to the primary jet. It is therefore likely that two sources may also exist for the streamwise vorticity generation in the air-tab case as in the solid-tab case [5]. The first source could be originated from deflection of the primary jet stream itself as it approached the injected airstream. The other source could be due to the primary jet that will eventually wrap behind the injected fluid column, forming streamwise vortices. At further downstream stations, the injected fluids with lower momentum would merge with the primary jet fluids via the streamwise vortices generated.

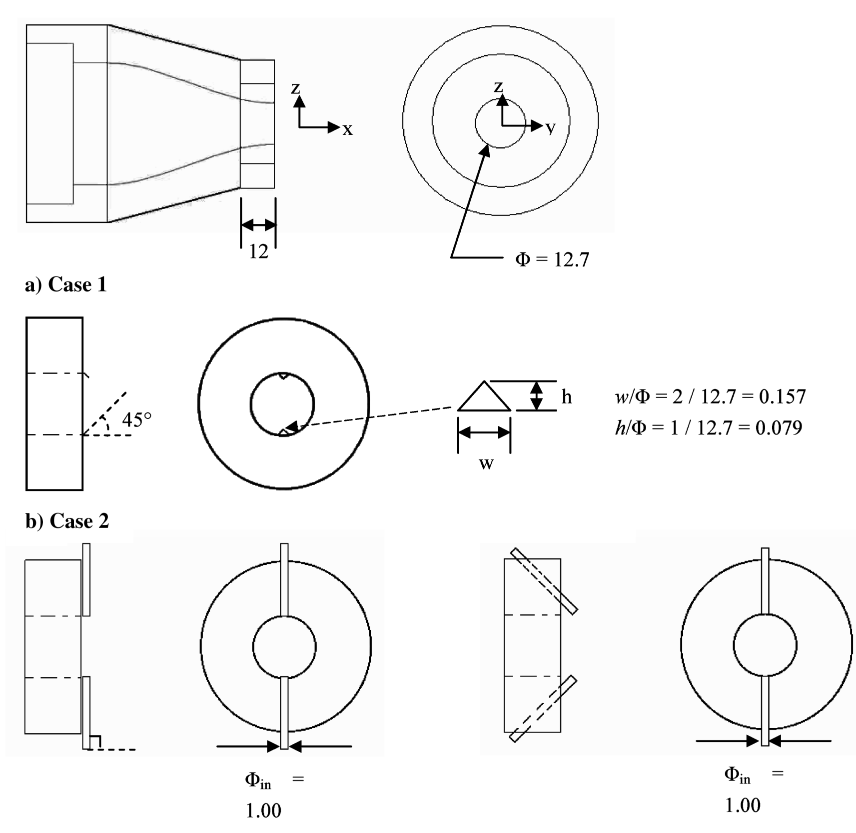

Fig. 1 Flow configurations under investigation (all dimensions are in mm).

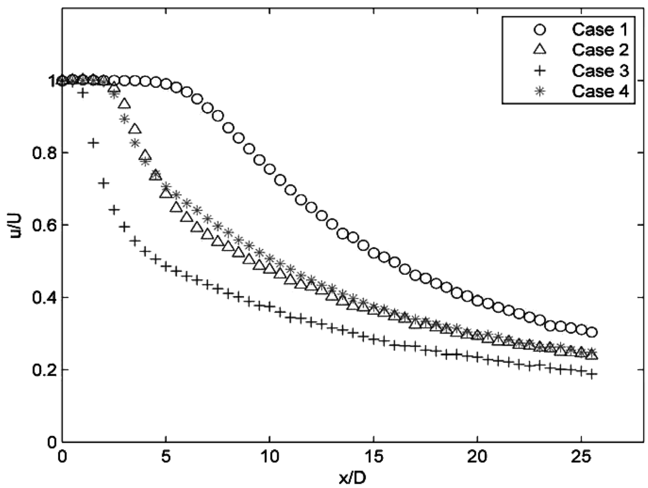

Fig. 2 Variation of the centerline velocity with downstream distance at $M = 0.8$ for the four different cases.

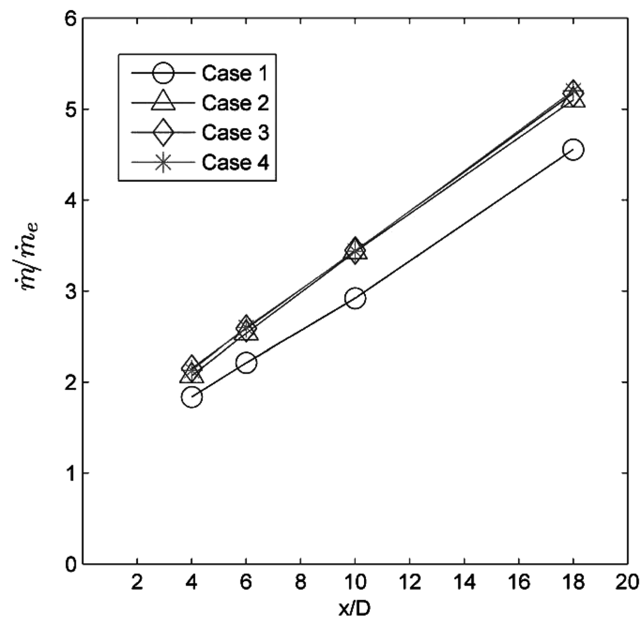

Fig. 3 Variation of normalized mass flux with downstream distance at $M = 0.8$ for four different cases.

C. Idealized Jet Thrust Consideration

The interaction between the primary jet and the air injected from the injector (air tab) occurs at a short distance downstream from the nozzle exit plane, but the air tab would not deteriorate the thrust of an aeroengine from the nozzle exit as with the solid tab. Moreover, in practical applications, the high-pressure air for the air tab would likely be tapped from the compressor of an aeroengine. The compressed air tapped from the compressor will reduce the amount of exhaust gas discharged from exhaust nozzle, resulting in thrust reduction.

Assuming one-dimensional flow at the nozzle exit, the thrust T of an exhaust nozzle is given by

$$T = \dot{m}U_e + (p_e - p_a)A_e \tag{1}$$

where $\dot{m}$ 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.

Because $\dot{m}U_e \gg (p_e - p_a)A_e$ [at ideal expansion, $(p_e - p_a)A_e = 0$], the thrust of a nozzle without a tab is

$$T \cong \dot{m}_e U_e \tag{2}$$

The thrust is proportional to the mass flow rate. If the air tab takes 2% of the air from the compressor, then the thrust lost in the nozzle exit is about 2% and becomes

$$T_{\text{tab-nozzle}} \cong 0.98\dot{m}_e U_e \tag{3}$$

This is the thrust generated from the exhaust nozzle with an air tab. However, the 2% of the air for the air tab would not be all wasted, as the high-speed air ejection of the air tab also made its contribution to the thrust. The thrust from an air tab (denoted by subscript at) is given by

$$T_{\text{at}} = \dot{m}_{\text{at}}u_{\text{at}} + (p_{\text{at}} - p_a)A_{\text{at}} \cong \dot{m}_{\text{at}}u_{\text{at}} \tag{4}$$

where u_{at} and p_{at} are the velocity and pressure at the ejector exit, and A_{at} is the area of the ejector exit.

The contribution to the thrust of the exhaust nozzle is

$$T_{\text{at}} = \dot{m}_{\text{at}}u_{\text{at}} \cos\theta \tag{5}$$

where θ is the attack angle of the air tab. If $\theta = 45$ deg and the amount of ejection air is 2% of the exhaust nozzle ($\dot{m}_{\text{at}} = 0.02\dot{m}_e$), then

$$T_{\text{at}} = \dot{m}_{\text{at}}u_{\text{at}} \cos\theta = 0.02\dot{m}_e u_{\text{at}} 0.707 = 0.01414\dot{m}_e u_{\text{at}} \tag{6}$$

If $u_{\text{at}} = 1.5U_e$, then

$$T_{\text{at}} \approx 0.02\dot{m}_e U_e \tag{7}$$

The total thrust for the airplane is

$$T_{\text{total}} = T_{\text{tab-nozzle}} + T_{\text{at}} = 0.98\dot{m}_e U_e + 0.02\dot{m}_e U_e = \dot{m}_e U_e \tag{8}$$

The air tab contributes 2% of the thrust of the exhaust nozzle to the total thrust. No thrust lost would then be caused by the air tab. If the air ejection has even higher velocity, such as $u_{\text{at}} = 2.2U_e$, then the total thrust of the exhaust nozzle could be increased by 1%, as the air tab would then contribute a total of 3% of the thrust under this circumstance.

Even when u_{at} is less than $1.5U_e$, as in the present experimental setup in which $u_{\text{at}} = 1.25U_e$, Eq. (8) can be rewritten as

$$\begin{aligned} T_{\text{total}} &= T_{\text{tab-nozzle}} + 2T_{\text{at}} = 0.984\dot{m}_e U_e \\ &\quad + 0.0155\dot{m}_e U_e(0.707) = 0.995\dot{m}_e U_e \end{aligned} \tag{9}$$

The loss of thrust would still be less than 0.05%. From the preceding simplified analysis, it is obvious that the air-tab technique would not create a large penalty on thrust if the injector has a higher velocity than the jet itself, but it can also increase the thrust further if the speed of the air tab is 1.5 time higher than that of an exhaust nozzle. For a typical solid tab, the loss by each tab was estimated to be at about 3% [5] and the losses were nonrecoverable. It should be noted that if the preceding analysis is applied to then case when $\theta = 90$ deg, it would imply no thrust contribution to the primary jet from the two injectors. However, this is unlikely because after the injected stream was diverted to align with the primary flow direction, it would eventually contribute to the total thrust.

IV. Conclusions

An air tab has been studied by injecting a small amount of gas with higher speed to the primary jet flow at certain attacking angles (45 and 90 deg). Comparison tests have been conducted with the traditional solid tabs. The blockage area for each solid tab amounted to about 0.8% of the exit area of the primary nozzle, and the tab base dimension was at the same order as the injector diameter. The amount of high-speed air at each injector was less than 1% of the mass flux of the primary nozzle. The comparisons between the solid-tab technique and air-tab technique reveal that the air-tab technique can enhance the jet mixing as effectively as the solid tab. The air tab achieved its effectiveness in mixing enhancement by air injection into the plume of the primary jet, forming a solid barrier similar to that of a solid tab and introducing streamwise vorticity to the jet flow. The effects are shown by a shorter potential core, faster decay of the centerline velocity, and larger air entrainment when air tabs were introduced to the primary nozzle.

Because the air-tab technique can obtain its effect on mixing enhancement with a small amount of air, it should not introduce much negative impact on the engine performance. The air-tab technique would not reduce the thrust of an aeroturbine engine, but it may be possible to even increase the total thrust when the ratio between the primary jet and the air-tab velocity is sized appropriately. This can be one of the advantages of an air tab over a traditional solid tab.

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