

Flow-field of the Excited Jet and Mixing in the Supersonic Flow

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The planar laser scattering and gas sampling were used to investigate the mixing of the excited CO₂ jet into the supersonic flow in this article. The jet was from the Hartmann-Sprenger tube, which was put into the traditional jet device. The jet was excited at three different frequencies and compared with the base case without excitation. The results shown that the better mixing with less total pressure loss could be obtained in the excited cases. The penetration was the deepest for 900Hz-excited jet while the number of the large-scale structures was the most in the 5 kHz-excited case. The excited jet didn't only take effects on the jet shear layer, but also influenced the boundary layer.

Nomenclature

f	=	Frequency
St	=	Dimensionless Frequency
C	=	Sound speed
D_j	=	Jet diameter
D_t	=	Tube diameter
D_e	=	Exit diameter
L	=	Tube Length
X	=	Tube standoff
R	=	Jet Pressure ratio (P_{jt}/Pa)

I. Introduction

THE efficient mixing and combustion must achieve in the limited space and time for the scramjet engine. The performance of scramjet would be controlled by the process and extent of mixing between fuel and air. It is very difficult to make the fuel penetrate into the supersonic flow deeply for forming the efficient mixing with air, which is the base of the efficient combustion.

Fuel injection could be transverse or parallel jet into the main flow. The transverse jet could bring the better penetration with the larger total pressure loss while the parallel jet could cause less total pressure loss with the worse penetration. According to the jet's drawbacks, researchers all over the world developed lots of methods to enhance mixing, such as the excited jet. The excited jet could be the source of disturbance to stimulate the fluctuation in the boundary layer to increase the instability. On the other hand, the excited jet also could amplify the vortex of the jet shear layer to induce large-scale structures.

Randolph^[1] investigated the effect of a forcing jet transverse into a supersonic cross flow. The frequency of the forcing jet was chosen to be 1 Hz. The results showed 12% increase in penetration when compared with a steady jet at the same peak exit pressure. Gutmark^[2] used the Mie scattering technique to visualize the flow field of the excited

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jet under high frequencies in the Mach 2 supersonic cross flow, and their results showed that the mixing was benefitted with excited jet..

II. Principle of H-S Tube

There are many methods to excite jet, and H-S tube is the useful one.

Hartmann developed an acoustic device that generates intense high frequency signal. The device, which was called as the Hartmann-Sprenger tube (H-S tube) later, consists of a supersonic under-expanded jet and a co-axial resonance tube which is closed at another end. The H-S tube could produce large amplitude rapid oscillations when the resonance tube was placed in the compressed region of the shock-rhombus. There are several important parameters, which are the pressure ratio of the jet R , the standoff distance X , the tube length L and the diameter of the jet D_j and the tube D_t , as shown in Figure 1.

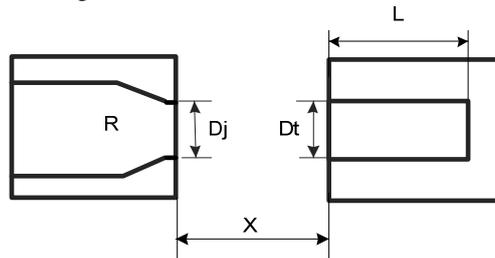


Figure 1 Sketch of the Hartmann-Sprenger tube

Sarobia^[3] demonstrated that there were three different modes of the H-S tube depending on the choices of these parameters as mentioned above. The first is the jet instability mode, which was excited for subsonic jets over a large range of X , excited at shear-layer initial instability frequency combined with the fundamental quarter wave of the resonance tube. The second mode, which was called as the jet regurgitant (JRG) mode, occurred due to the periodic swallowing and discharging of the jet flow by the resonance tube at the fundamental tube resonance frequency ($f = C/4L$, where C is the sound speed in the tube). The third was called as screech mode, which was a high-frequency mode and occurred due to the formation of a normal shock in the front of the resonance tube. The strength and location of this mode was governed by the pressure ratio R and the standoff distance X .

Compared with the other two modes, the JRG mode is more controllable and can produce stronger oscillation. But the estimated equation of oscillation frequency in the reference had a large error compared with the measured value, especially in the case of the small diameter of tube. Therefore, Gu^[4] modified the estimated equation according to the experimental data, in order to design more accurate frequency for the case of small diameter of the resonance tube, as shown in Figure 2.

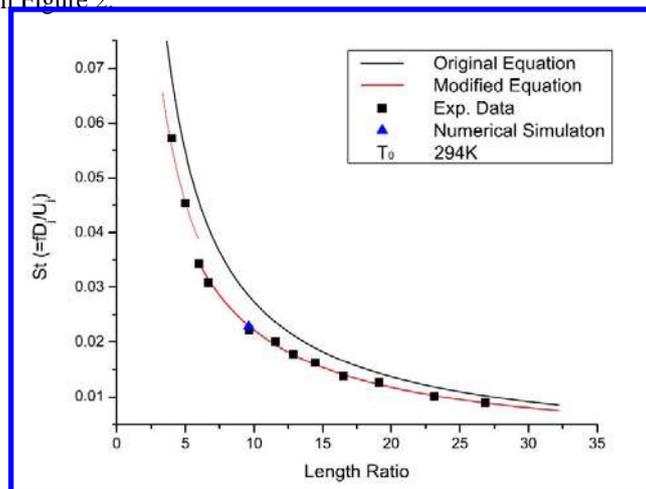
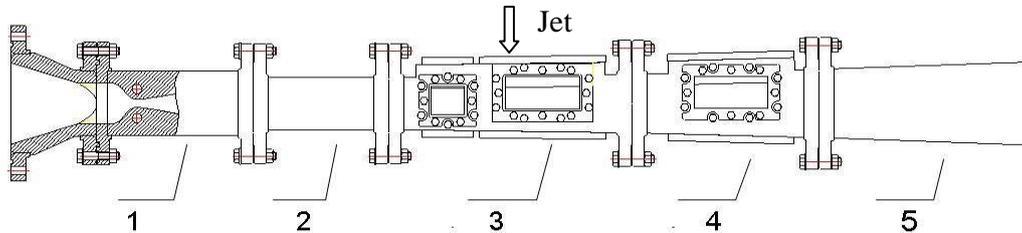


Figure 2 Comparison of estimated and measured frequency^[4]

III. Experimental Setup

The experiments were performed in the direct-connection supersonic combustion test facility, shown in **Figure 3**, in the Institute of Mechanics, Chinese Academy of Science. The air flow with high pressure and high temperature which the setup needed was supplied by the heater, and was accelerated to Mach 2.5 by the supersonic nozzle, then entered into the isolator, 1st test section, 2nd test section and nozzle in sequence.



1-Facility Nozzle 2-isolator 3-1st test section 4-2nd test section 5-Nozzle

Figure 3 Experimental Setup

The structure of the excited jet is shown in the Figure 4, whose exit is about 5mm. The input to the device is CO₂ flow with constant mass flow rate at a certain pressure and temperature. The output is a circular jet with fluctuating flow in the axial direction superimposed on the mean field. The H-S tube was tuned to the JRG mode while the desirable frequencies could be obtained by changing the tube length L with other parameters fixed. The cases were investigated under excited frequencies at 900Hz 1.3 kHz and 5 kHz, which compared with the base case without excitation.

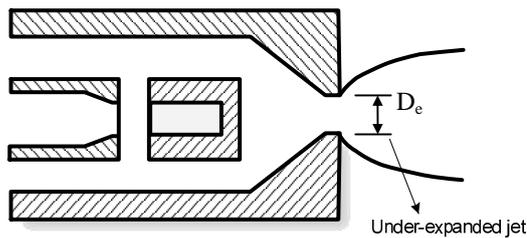


Figure 4 Sketch of the excited jet

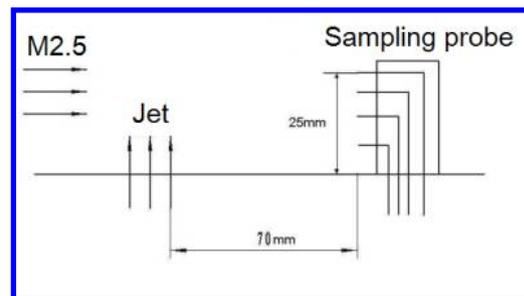


Figure 5 Location of the sampling probe

The parameters of main flow in the experiments were Mach 2.5, the total temperature with 960K~980K and the total pressure with $1.26\text{MPa} \pm 6\%$. The total pressure and total temperature of CO₂ jet were 0.65MPa and 300K respectively. The location of the jet was shown in Figure 3 while the sampling probe was fixed downstream of the jet, as shown in Figure 5. The nano-particles were put into the CO₂ jet and the planar laser scattering was used to visualize the flow-field of CO₂ jet. According to the work mentioned above, H-S tube was used as high frequency actuator and was put into the traditional jet device, which called the excited jet, in order to generate the jet with fluctuation at a certain frequency. This article studied the effects of the excited jet on the mixing in the Mach 2.5 supersonic cross flow.

IV. Results

A. Instantaneous scattering images

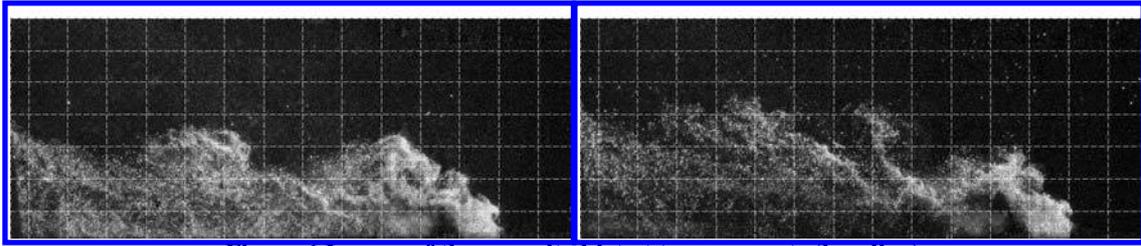


Figure 6 Images of the unexcited jet at two moments (baseline)

The flow structure of unexcited jet at two different moments was shown in Figure 6. The maximum depth of penetration of the CO₂ jet was about $3D_e \sim 4D_e$. There were large-scale structures in the jet shear layer, whose wavelength was between $5D_e \sim 6D_e$. The depth of penetration would alternate between the big and the small with the large-scale structures existing, and there were also lots of small-scale vortices in the jet shear layer due to the Kelvin-Helmholtz instability. The CO₂ jet would be spread into the supersonic cross flow by those small-scale vortices which transported by the large-scale structures. Above all, the large-scale structures took big effects on the process and the extent of the mixing between CO₂ and air.

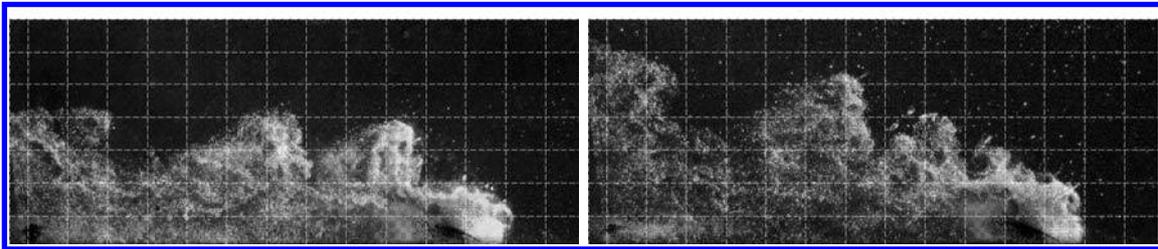


Figure 7 Images of the 900Hz-excited jet at two moments

The images of the jet excited at 900Hz were shown in Figure 7. The case of the jet excited at 1.3 kHz was similar to this one. The penetration of the CO₂ jet became much deeper than the base one, which increased to $4D_e \sim 6D_e$. Compared to the base one, the number of the large-scale structures also increased.

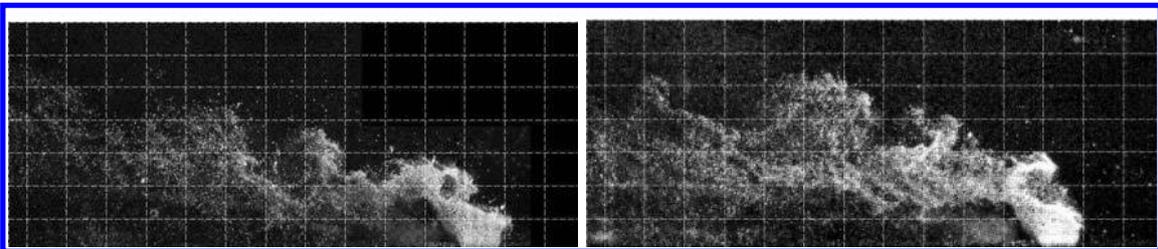


Figure 8 Images of the 5 kHz-excited jet at two moments

The mixing of the jet excited at 5 kHz was shown in Figure 8. The penetration in this case was deeper than the base one, but little less than one of the 900Hz-excited case. The number of the large-scale structures was the most of all the case.

According to the results of scattering, the following conclusion could be obtained. First, the mixing was better in the case of the excited jet because of the deeper penetration and the more large-scale structures. Second, the penetration was the deepest in the 900Hz-excited case while the number of the large-scale structures was the most in the 5 kHz-excited case. Third, the excited jet took effects on the jet shear layer.

B. The profile of total pressure loss and the CO₂ concentration

The information of the instantaneous flow was obtained from the scattering images, and the time-averaged information could be obtained from the profile of total pressure loss and CO₂ concentration.

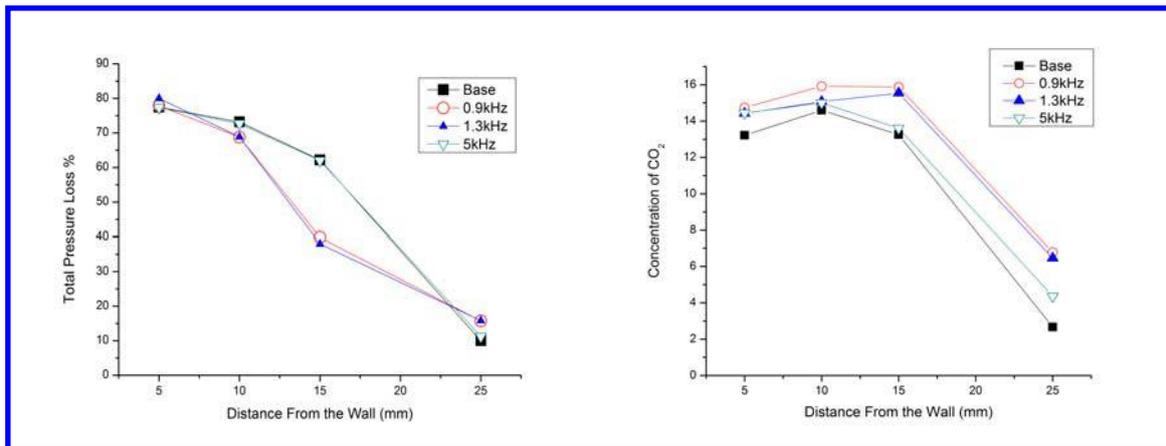
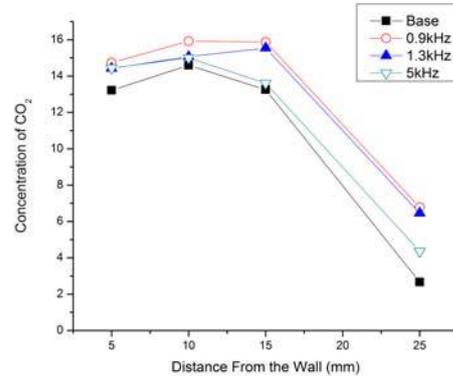


Figure 9 The profile of total pressure loss Figure 10 The profile of CO₂ concentration



The probe location was shown in Figure 5. The profile of the total pressure loss and CO₂ concentration were shown in Figure 9 and Figure 10 respectively. The CO₂ concentration at all four points was bigger in the excited case than in the base. The total pressure loss were close in all the cases at the most points, but the total pressure loss in the 900Hz-excited and 1.3kHz-excited cases were only half of the base at the point of 15mm away from the wall. Therefore, the results shown that the penetration in the excited cases were deeper than base with less total pressure loss.

The maximum of the CO₂ concentration in the 900Hz- and 1.3 kHz-excited cases was shifted from 10mm away from the wall to 15mm away from the wall. It might result from the flow lifted by the boundary layer due to the excited jet.

V. Conclusion

The experimental investigation were carried out for the excited jet into M2.5 flow. According to the scattering images and the profile of the total pressure loss and CO₂ concentration, the following conclusion could be:

- 1) The better mixing with less total pressure loss could be obtained in the excited cases, such as the deeper penetration, the more large-scale structures and the bigger CO₂ concentration.
- 2) The penetration was the deepest in the 900Hz-excited case while the number of the large-scale structures was the most in the 5 kHz-excited case.
- 3) The excited jet didn't only take effects on the jet shear layer, but also influenced the boundary layer.

Acknowledgments

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