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The Effect of the Secondary Annular Stream on Supersonic Jet

Kwon Hee Lee, Toshiaki Setoguchi, Shigeru Matsuo
Department of Mechanical Engineering, Saga University,
Honjo-machi, Saga-shi, Saga 840-8502, Japan
Hyeu Dong Kim*
School of Mechanical Engineering, Andong National University,
Songchun-dong, Andong 760-749, Korea

The present study addresses an experimental investigation of the near field flow structures of supersonic, dual, coaxial, free, jet, which is discharged from the coaxial annular nozzle. The secondary stream is made from the annular nozzle of a design Mach number of 1.0 and the primary inner stream from a convergent-divergent nozzle. The objective of the present study is to investigate the interactions between the secondary stream and inner supersonic jets. The resulting flow fields are quantified by pitot impact and static pressure measurements and are visualized by using a shadowgraph optical method. The pressure ratios of the primary jet are varied to obtain over-expanded flows and moderately under-expanded flows at the exit of the coaxial nozzle. The pressure ratio of the secondary annular stream is varied between 1.0 and 4.0. The results show that the secondary annular stream significantly changes the Mach disc diameter and location, and the impact pressure distributions. The effects of the secondary annular stream on the primary supersonic jet flow are strongly dependent on whether the primary jet is under-expanded or over-expanded at the exit of the coaxial nozzle.

Key Words : Compressible Flow, Shock Wave, Supersonic Jet, Mach Disc, Coaxial Nozzle

Nomenclature

D	: Diameter (mm)
d_m	: Mach disc diameter (mm)
p	: Pressure (kg_f/cm^2)
p_{impact}	: Impact pressure (kg_f/cm^2)
x	: Axial distance (mm)
r	: Radial distance (mm)
ξ	: Pressure ratio

Subscripts

a	: Ambient state, or annular shock wave
e	: Nozzle exit
m	: Mach disc
0	: Stagnation state
p	: Primary jet
s	: Secondary stream or static condition

1. Introduction

Single supersonic free jet discharging from a nozzle or an orifice has been often employed in various industrial and engineering processes. A number of studies have been done to detail the major characteristic features of the supersonic jets. According to these previous works (Love et al., 1959 ; Kim et al., 1996 ; Katanoda et al. 2000), the single supersonic jet is usually specified by the jet pressure ratio that determines the barrel shock structure, Mach disc, the jet boundary configuration, etc.

In recent years, there has been a growing interest with regard to engineering applications of the supersonic coaxial jet to the combustion instability of rocket engine (Vu et al., 1982), the

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* Corresponding Author,
E-mail : kimhd@andong.ac.kr
TEL : +82-54-820-5622; **FAX** : +82-54-823-5495
School of Mechanical Engineering, Andong National University, Songchun-dong, Andong 760-749, Korea.
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suppression of jet noise (Dosanjh et al., 1971 ; Papamoschou, 2002), and improvement of the work performance and efficiency in cutting or welding, (Niu, 1996 ; Chen et al., 2000), etc. In usual, these applications require uniform supersonic jets with desirable flow properties and stable impact pressure distribution extending up to many nozzle diameters downstream along the jet axis. However, the detailed flow structures of supersonic, dual, coaxial, jet are not yet understood well since the secondary stream remarkably influences the major characteristics of the primary jet, consequently leading to highly complicated flow fields due to the strong interaction between both streams.

There have been a few of works about the supersonic coaxial jet flows. These works have been mainly concentrated on the near field flow structures of the coaxial jet, but the existing data are too sparse, and even ambiguous. Buckely et al. (1975) have argued that the location of the Mach disc generated in a supersonic, dual, coaxial jet will not be altered since the axial Mach number distributions upstream of the Mach disc are independent of the conditions of the external streams. Masuda et al. (1994) and D'Attorre et al. (1965) have reported that the presence of the secondary annular jet has a favorable effect for reducing the diameter of Mach disc formed in the primary inner jet.

Meanwhile, Narayanan et al. (1992) and Rao et al. (1996) have argued that the Mach disc location and its diameter will be strongly dependent on the pressure ratio of the secondary annular stream, since it changes the Mach number distribution upstream of the Mach disc. This is an obvious contrast to the argument made by Buckely et al. (1975).

In recent, Cutler et al. (2001) have made some experimental works to make clear these problems. They have measured the pitot pressure distributions of the supersonic coaxial jet and made a computational study to represent their experimental results. However, they did not give any comprehensive descriptions with regard to the secondary stream effects and the Mach disc characteristics. Further study is needed to detail the supersonic dual, coaxial jet flows.

The present study addresses an experimental result to investigate the effects of the secondary stream on the primary supersonic jets. The secondary stream is made from a secondary annular nozzle with a Mach number of 1.0, and the supersonic primary jet is discharged from a convergent-divergent nozzle with a design Mach number of 1.5. The flow fields are quantified by pitot impact and static pressures and are visualized by using a shadowgraph optical method.

2. Experimental Apparatus and Method

Experiment is conducted using a simple test rig, as schematically shown in Fig. 1. The test facility consists of a compressor, a reservoir tank, a primary and secondary plenum chambers. Compressed dry air in the reservoir tank with a volume of 6.0 m^3 is separately supplied into the primary and secondary plenum chambers upstream of the coaxial nozzle. The pressures in each plenum chamber are independently varied using a pressure regulator. The details of the coaxial nozzles employed are presented in Fig. 2. The primary inner circular nozzle has a throat diameter of D_t=8.0 mm, and an exit diameter D_e=8.7 mm. The secondary stream is discharged from an annular outer convergent nozzle that has four axial inlet ports that are connected with the plenum chambers.

The primary p_{0p} and secondary plenum chamber p_{0s} pressures are varied using the pressure regulator. The pressure p_e at the exit of the primary nozzle is dependent on both p_{0p} and p_{0s}. The jet flow is over-expanded as p_e is less than the back pressure p_a which is atmospheric pressure (=1 atm) during test, and it is under-expanded as p_e is higher than p_a. In the present experiments, the pressure ratio of p_e/p_a is varied between 0.79 and 3.70. The pressure ratio of the secondary annular stream which is given as p_{0s}/p_a is also varied between 1.0 and 4.0. These pressure ratios are defined as ξ_p and ξ_s, respectively. Thus, ξ_s= 1.0 means no secondary stream, while ξ_p=1.0 means the perfect expansion of the supersonic

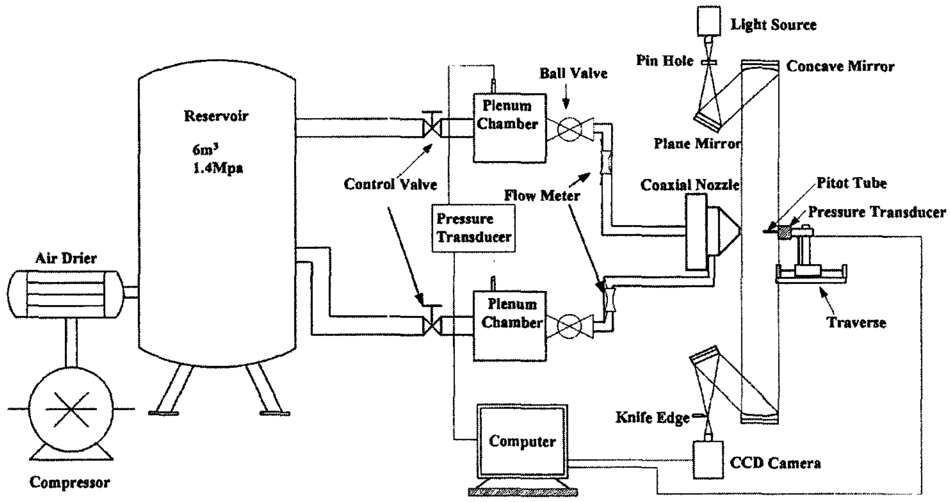
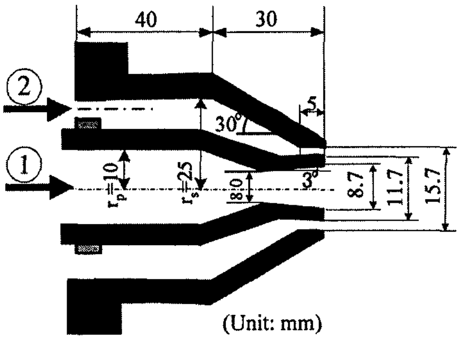


Fig. 1 Schematic outlook of experimental facility



① Axial inlet for primary jet
② Axial inlet for secondary jet

Fig. 2 Details of dual, coaxial, nozzle ($M_d=1.5$)

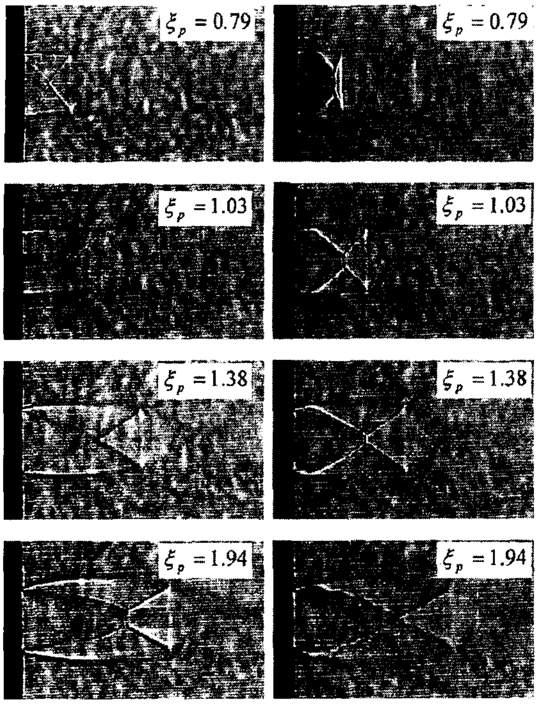
inner jet at the exit of coaxial nozzle. A fine pitot probe with an outer diameter of 0.8 mm is employed to measure the impact pressures in both the radial and axial directions. A cone static probe has a half-angle of 10 deg and its diameter is 1.26 mm. Four static holes of a diameter of 0.3 mm are drilled to measure local static pressures.

The pressure ports were located 14 times of probe diameter from the tip and connected to a pressure transducer. These probes are installed onto a 3-way traverse system, which is controlled by a PC. The moving speed of the probe is negligibly low to ensure that the probe movement does not significantly disturb the coaxial jet flow.

The pressures and temperatures in the plenum chambers are measured using a pressure transducer and a thermocouple, respectively, which are monitored by a PC. The temperatures are nearly at atmospheric condition in experiments so that the air temperature effect is negligible in the present experiments. Calibrations of the pressure transducers are made prior to each test. The uncertainty in pressure measurements is estimated to be less than ±1.0%, while it is estimated to be about ±2.5% in taking the experimental data of the diameter and location of the Mach disc from a number of shadowgraph pictures. The reservoir tank provides approximately 50 seconds for steady run.

3. Results and Discussions

Typical shadowgraphs are presented to reveal the near field flow structures of both single and coaxial free jets (see Fig. 3). For the single jet ($\xi_s=1.0$) without the secondary annular stream, the flow is strongly dependent on ξ_p. At $\xi_p=0.79$, the jet is slightly over-expanded at the exit of nozzle and the oblique shock wave system formed inside the nozzle propagates outside toward the jet boundaries, and reflecting from the jet boundaries to produce the repeated pressure



(a) Single free jets ($\xi_s = 1.0$) (b) Coaxial free jets ($\xi_s = 1.5$)

Fig. 3 Shadowgraph pictures showing supersonic jet

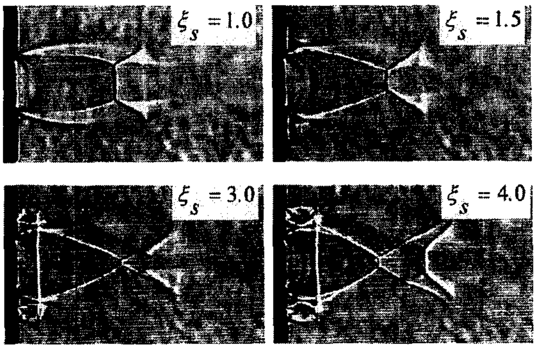


Fig. 4 Shadowgraph pictures showing coaxial jet ($\xi_p = 3.70$)

waves. At $\xi_p = 1.03$, the jet is nearly close to the perfect expansion and very weak oblique shock waves are formed at the exit of nozzle, and the jet boundaries are nearly parallel to the nozzle axis. As ξ_p increases over 1.03, the jet flow is underexpanded and strong oblique shock waves, called as a barrel shock, appear downstream of the exit of the nozzle. It seems that the barrel shock becomes stronger as ξ_p increases, and a Mach disc that is formed by the reflection of the barrel shock on the jet axis appears at $\xi_p = 1.94$. In the present experiment, the Mach disc occurred as ξ_p is over 1.94 (Addy, 1981).

The effects of the secondary annular stream on the single free jet flow described above are shown in Fig. 3(b), where ξ_s is fixed constant at 1.5. In this case, it should be noted that the secondary stream is subsonic at the exit of the coaxial annular nozzle. It seems that the secondary annular stream remarkably changes the primary jet structures. In contrast to Fig. 3(a) , the Mach disc is formed for all of ξ_p values applied. For ξ_p below 1.94, the Mach disc did not appear in the single jet. It is, thus, believed that the secondary stream acts as a pressure boundary condition around the primary jet flow and then encourage an expansion of primary jet boundary. It is interesting to note that at $\xi_p = 1.94$, the secondary stream remarkably reduces the Mach disc, compared with Fig. 3 (a). The present visualization pictures apparently show that the effect of the secondary stream on the Mach disc is strongly dependent on ξ_p value, i.e., the expansion state of the primary jet at the exit of nozzle.

Figure 4 shows the effects of ξ_s on the primary jet flow, where ξ_p is fixed at 3.7. It is found that ξ_s remarkably changes the diameter and location of the Mach disc, influencing the spreading of the primary jet. It is interesting to note that an annular shock wave occurs in the secondary annular stream as ξ_s is over a certain value. In order to quantify the Mach disc behaviors described above, Fig. 5 represents the relationship between the Mach disc diameter d_m and ξ_s. For ξ_p values below 1.38, the Mach disc diameter increases with ξ_s, while at $\xi_p = 1.94$, it reduces in the range of ξ_s below 1.5, but increases again with ξ_s in the range over 1.5. In general, the diameter of the Mach disc depends on the width of the jet boundary layer. It is believed, therefore, that the secondary stream have influence on the width of the jet boundary layer and effect on the Mach disc is strongly dependent on ξ_p value, as mentioned previously.

Figure 6 shows the relationship between the location X_m of the Mach disc and ξ_s, where

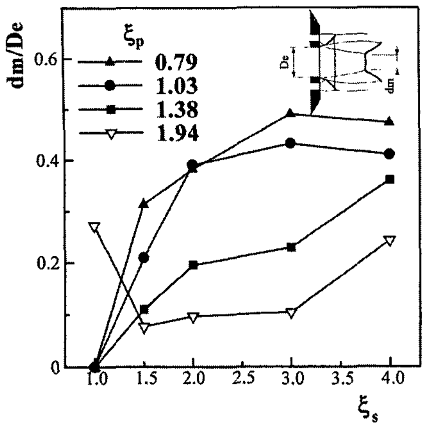


Fig. 5 Mach disc diameter vs. ξ_s

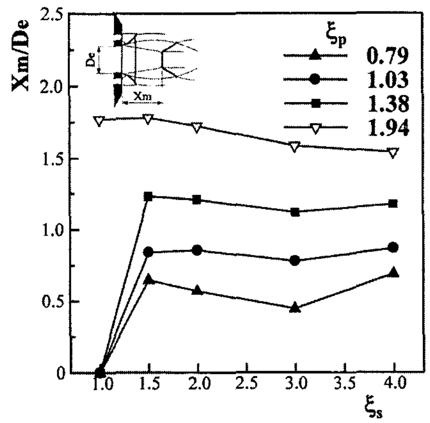


Fig. 6 Mach disc location vs. ξ_s

X_m is measured from the exit of the nozzle, and is normalized by the exit diameter De of the primary nozzle. At $\xi_p=1.94$, it seems that the secondary stream causes the Mach disc to slightly move upstream as ξ_s increases, while for ξ_p value below 1.38, the Mach disc location suddenly changes with ξ_s and then slightly moves upstream before moving downstream again for high ξ_s values. It is quite difficult to generalize these tendencies that found in the Mach disc location with ξ_s. However it here is obviously known that the Mach disc strongly depends on both ξ_s and ξ_p. The effects of the secondary annular stream on the Mach disc are dependent on whether the primary jet is over-expanded or under-expanded.

For a fixed value of $\xi_s=4.0$, Fig. 7 shows the effects of ξ_p on the shock structures in the coaxial jet flow. The annular shock is clearly observed downstream of the coaxial nozzle. At ξ_p over 1.38, the oblique shocks form in the secondary annular stream, but these do not occur at $\xi_p=$ 0.79 and 1.03. It is found that the oblique shocks interact with the annular shock and the barrel shock of the primary jet, and consequently the location of the annular shock wave changes with ξ_p. Fig. 8 presents the variation of the annular shock location with ξ_p and ξ_s, where Xa refers to the distance of the annular shock from the exit of nozzle. For a given ξ_p, the location of the annular shock wave increases with ξ_s, while for a given ξ_s, the annular shock wave slightly moves upstream with ξ_p, consequently influencing the spreading of the secondary jet. Fig. 9 shows the impact pressure distributions along the coaxial jet axis. In Fig. 9(a), the impact pressure distributions are significantly varied depending on

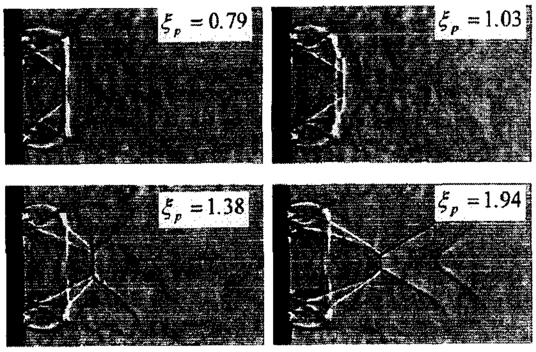


Fig. 7 Shadowgraph pictures showing coaxial jet ($\xi_s=4.0$)

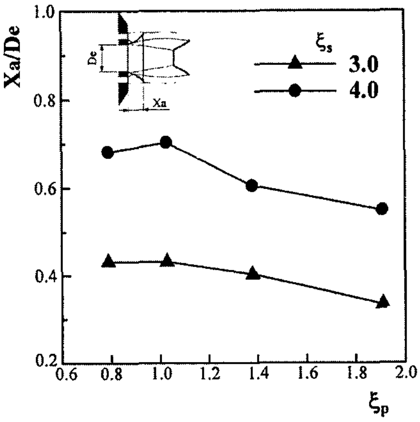
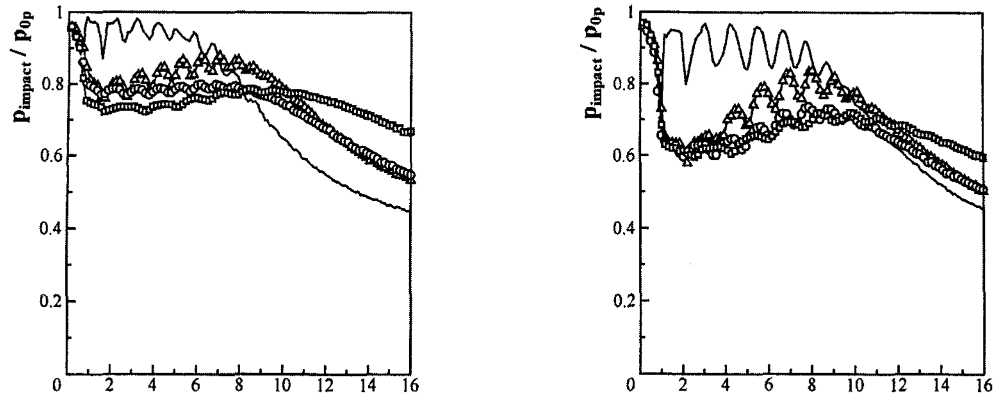
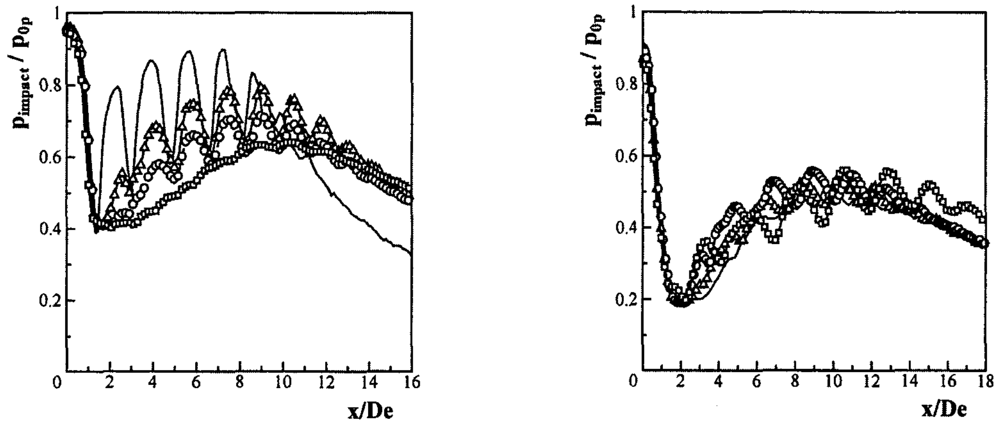


Fig. 8 Annular shock wave location vs. ξ_p



(a) $\xi_p=0.79$ (b) $\xi_p=1.03$



(c) $\xi_p=1.38$ (d) $\xi_p=3.70$

Fig. 9 Impact pressure distributions along the nozzle axis (ξ_s : —— 1.0 ; —△— 1.5 ; --○-- 2.0 ; —□— 4.0)

ξ_s. For no secondary annular stream of $\xi_s=1.0$, the impact pressure highly fluctuates with the axial distance, as was found in a supersonic single jet (David, 1995). With the secondary annular streams, it suddenly decreases and then increases with some extent of fluctuations, before monotonously decreasing in which the flow is decelerated to subsonic velocity. The impact pressure fluctuations increase with ξ_p. At $\xi_p=3.70$, the primary jet is comparatively highly under-expanded at the exit of nozzle. In this case, it seems that ξ_s does not significantly change the impact pressure distribution, compared with the cases of lower ξ_p.

Figure 10 shows the radial distributions of the impact pressures for different ξ_p and ξ_s values. At x/De=0.1, there seems to be no any notable effect of ξ_s on the impact pressure distributions, but at x/De≥1.0, ξ_s remarkably changes the radial impact pressure distributions. In Fig. 10 (a), the impact pressures on the jet axis decrease

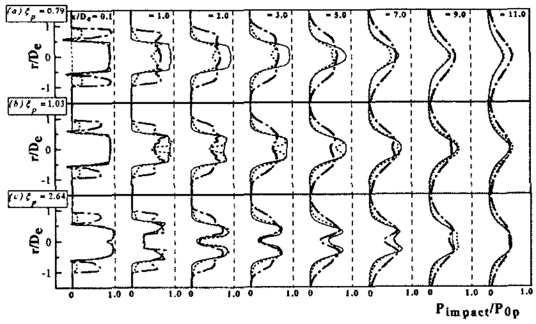
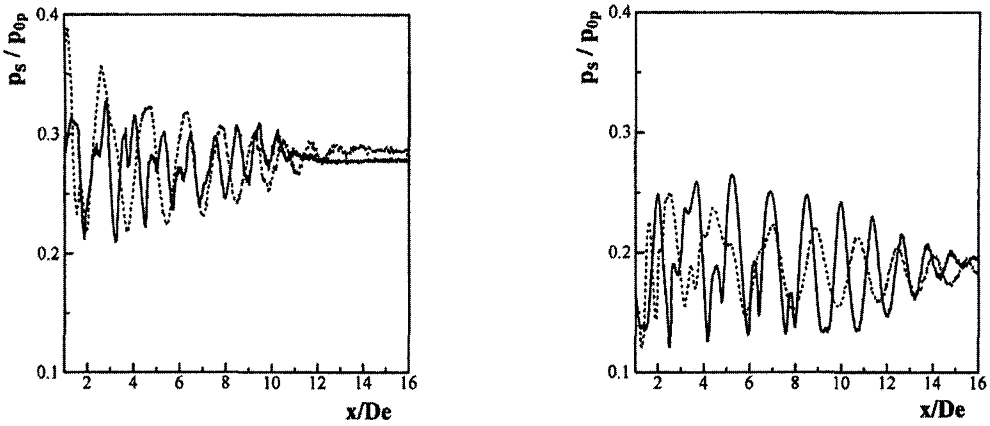


Fig. 10 Impact Pressure distributions in radial direction (ξ_s : —— 1.0 ; ------ 1.5 ; —·— 3.0)



(a) $\xi_p=1.03$ (b) $\xi_p=2.64$

Fig. 11 Static pressure distributions along the nozzle axis (ξ_s : —— 1.0 ; ------ 4.0)

with ξ_s in the range below x/De=7.0, but for $\xi_s=3.0$, those increase with ξ_s in the range over x/De=7.0, compared with no secondary annular stream of $\xi_s=1.0$. The radial gradient in the impact pressure distributions near the coaxial jet boundaries reduces as ξ_s increases. At $\xi_p=2.64$, ξ_s does not influence the impact pressure on the jet axis in the range below x/De=5.0. From the present impact pressure distributions, it is believed that the mixing effect of the coaxial jets is improved as ξ_s increases and ξ_p decreases.

Fig. 11 shows the static pressure distributions along the coaxial jet. The static pressures highly fluctuate with the distance ; at $\xi_p=1.03$, the static pressure fluctuations amount to about 40% of p_{0p} and those are continued up to x/De=about 14.0. In this case, the secondary annular stream slightly increases the static pressure fluctuations. At $\xi_p=2.64$, it seems that the static pressure fluctuations increase and are continued up to longer axial distance, compared with the case of $\xi_p=1.03$. The secondary annular stream decreases the static pressure fluctuations in contrast to the case of $\xi_p=1.03$. Until now, almost all of works on the supersonic jets have neglected these static pressure fluctuations so that the Mach numbers could have deduced by only the impact pressure measurements. The present data show that the coaxial jet has strong radial static pressure gradients that should be involved to investigate the major characteristics of the supersonic jets.

4. Concluding Remarks

The effects of the secondary annular stream on the supersonic jet are investigated using the impact and static pressure measurements. The flow field is visualized to obtain qualitative structures of the shock waves that are formed in the supersonic coaxial jets. The present study showed that the secondary annular stream significantly changes the supersonic inner jet. It is difficult to generalize the secondary stream effects since those are strongly dependent on whether the primary jet is under-expanded or over expanded at the exit of nozzle. Several major conclusions obtained are summarized ;

(1) The secondary annular stream changes the shock wave structures and the impact pressure distributions of the supersonic coaxial jet, although it does not influence the impact pressure distribution upstream of the Mach disc.

(2) The secondary annular stream significantly changes the diameters and location of the Mach disc, depending on both ξ_s and ξ_p, and the secondary annular stream effect is strongly dependent on whether the primary jet is over-expanded or under-expanded.

(3) The secondary annular stream significantly affects the impact pressure distributions when the pressure ratio of the primary jet is comparatively low, thus the flow being over-expanded or weak-

ly under-expanded. But it does not greatly influence the impact pressure distributions when the jet flow is highly under-expanded.

(4) The static pressure fluctuations that amount to over several ten per cent of the upstream stagnation pressure occur in the supersonic coaxial jet. The secondary annular stream reduces the static pressure fluctuations.

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