Aerodynamic Characteristics of Underexpanded Coaxial Impinging Jets*

Wataru MASUDA** and Eiji MORIYAMA***

Flow behavior of underexpanded coaxial impinging jets is investigated experimentally and simulated numerically by solving compressible Navier-Stokes equations. Two converging coaxial nozzles, one with outer annular jet parallel to an inner circular one, and the other with inclined annular jet, are fabricated and tested. The flow visualization using the shadowgraph method, the pressure measurements at the impinging surface and the numerical simulation show that the presence of the outer annular jet has favorable effects for reducing the diameter of the Mach shock disk which is formed in the inner jet. However, the maximum pressure on the impinging flat plate obtained in the present study is lower than that produced previously by a simple annular jet, showing that the simple annular jet can be more favorable for laser cutting.

Key Words: Supersonic Flow, Jet, Coaxial Jet, Shock Wave Laser Cutting

1. Introduction

Most material cutting techniques with a focussed laser beam utilize a gas jet to remove molten and vaporized material from the kerf. Fieret et al.⁽¹⁾ demonstrated a strong correlation between the aerodynamic characteristics of the impinging jet and the laser cutting performance. They showed that the maximum laser cutting speed is positively correlated with the local pressure at the impinging point on the workpiece P_{jc} . However, conventional circular-tipped nozzles cannot produce very high P_{jc} by simply raising the plenum pressure P_0 , since the formation of a Mach shock disk (MSD) in the jet severely reduces the stagnation pressure. In our previous studies⁽²⁾⁻⁽⁴⁾, therefore, the aerodynamic characteristics of underexpanded annular impinging jets were studied experimentally, and it was shown that the annular impinging

jet has great potential for laser cutting, especially with mirror focussing.

The coaxial jet is also expected to be favorable as an assist jet, since the presence of the outer annular jet may suppress the formation of MSD within the inner jet. In the present investigation, the flow behavior of underexpanded coaxial impinging jets is studied experimentally and simulated numerically by solving compressible Navier-Stokes equations. Two converging coaxial nozzles, one with an outer annular jet parallel to an inner circular one, and the other with an inclined annular jet, are fabricated and tested. Experiments are performed with various combinations of the plenum pressures of the outer annular nozzle and inner circular nozzle, and the distance between the nozzle exit and the impinging plate. The measurements include the surface pressure of an impinging flat plate and flow visualization using the shadowgraph method.

2. Experiment

Two converging coaxial nozzles are fabricated in the present investigation. The important features of the nozzle arrangement are shown in Fig. 1. Both the

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** Faculty of Engineering, Nagaoka University of Technology, 1603-1 Kamitomioka, Nagaoka 940-21, Japan

*** Graduate Student, Nagaoka University of Technology

outer annular nozzle and the inner circular nozzle are convergent. The specifications of the two coaxial nozzle contours (I and II) are summarized in Table 1 where d is the diameter of the inner nozzle, D_i and D_o are the inner and outer diameters of the annular nozzle, respectively, and α is the ejection angle of the annular jet. It is noted that the outer annular jet of Nozzle I is ejected parallel with the inner jet. On the other hand, the annular jet of Nozzle II collides strongly with the inner jet. Air at room temperature, which is supplied from air cylinders, is used as the working gas. Since the stagnation pressures of the outer annular nozzle P_{0o} and the inner circular nozzle P_{0i} can be regulated independently, various combinations of P_{0o} and P_{0i} are available. For a reservoir pressure P_{0i} of 5×10^5 Pa, the Reynolds number based on the sonic conditions and d is 3.9×10^5 .

The solid plate which simulates the workpiece is a square of 120×120 mm², as shown in Fig. 2. The square probe with a pressure tap of 0.2 mm in diameter at the center can be scanned transversely to the jet axis with an error of 0.02 mm using pulse motors which are controlled by a personal computer. The distance H between the nozzle exit plane and the square probe can be arranged manually. The reservoir pressures P_{0i} and P_{0o} , and the surface pressure P_j are measured within the error of 1% by pressure transducers, whose signals are digitalized and processed by a personal computer. The atmospheric pres-

sure P_a is measured by a mercurial manometer. Visualization of the jet is performed by the shadowgraph method. The shadowgraphs are obtained using a spark light source.

3. Numerical Method

The coaxial jets are simulated numerically by solving unsteady, compressible, axisymmetric Navier-Stokes equations and turbulence model equations⁽⁵⁾ which were developed by Coakley. In the present investigation, a finite volume method with quadrilateral cells is used to solve these equations. The Roe flux difference splitting scheme⁽⁶⁾ is applied to estimate the fluxes across each side of the cells and the resulting equations are integrated with respect to time using a point implicit method⁽³⁾.

4. Results

4.1 Jets from circular-tipped nozzle

Figure 3 shows the shadowgraphs of free jets

Table 1 Specifications of the nozzle contour

Nozzle Type	α	β_1	β_2	β_3	h_1	h_2	ϕD
	[deg.]				[mm]		
Nozzle I	0	90	60	45	12.5	5.0	10.0
Nozzle II	40	50	60	50	9.5	4.8	6.0

Fig. 1 Coaxial nozzle contour

Fig. 2 Schematic diagram of the experimental apparatus

(a) $P_{0i}/P_a = 3$ (b) $P_{0i}/P_a = 5$ (c) $P_{0i}/P_a = 7$ (d) $P_{0i}/P_a = 9$

Fig. 3 Shadowgraphs of free jets issuing from circular-tipped nozzle (inner nozzle of Nozzle II)

issuing from the inner nozzle of Nozzle II. The characteristics of the underexpanded free jet issuing from such a circular-tipped nozzle have been very well studied. At lower reservoir pressure ($P_{0i}/P_a=3$), a conical converging shock wave is formed from the inner edge of the nozzle exit, as shown in Fig. 3(a). This shock can intersect at the axis and reflect at the jet boundary a number of times. For higher pressure ratio P_{0i}/P_a , the converging shock becomes curved and is too strong to allow for the regular intersection. In this case, a normal Mach shock disk (MSD) is formed in the jet, as shown in Figs. 3(b)-(d). The flow just downstream of the MSD is subsonic but flow that does not cross the MSD can be supersonic. The MSD shifts to the downstream direction and the diameter becomes large as P_{0i}/P_a is raised.

The surface pressure on the impinged plate P_j is strongly influenced by the shock structure in the jet. Figure 4 shows the surface pressure at the jet axis P_{jc} as a function of both P_{0i}/P_a and H/d . Fieret et al.⁽¹⁾ demonstrated that higher P_{jc} is necessary to attain higher cutting speed. It is considered that a higher P_{jc} is favorable for laser cutting, since a larger amount of gas at the central stagnation point on the plate can intrude into the kerf. For lower P_{0i}/P_a , Fig. 4 shows that the interaction of shocks with the impinged plate results in P_{jc}/P_a that shows large periodical variation with H/d . This variation can be identified with the flow features depicted in Fig. 3(a). Figure 4 also shows that the periodic variation disappears as P_{0i}/P_a is raised due to the formation of the MSD. Since the flow which crosses the MSD suffers a large drop in the stagnation pressure, the rise in P_{0i} does not necessarily lead to the higher P_{jc} . Although considerably high P_{jc} can be obtained at small H/d , the optical components are vulnerable to debris⁽⁴⁾. Therefore, Fieret et al.⁽¹⁾ recommended the use of P_{0i} which does not create the MSD, and set the circular nozzle at its optimum cutting height.

Fig. 4 Dependence of P_{jc}/P_a generated by circular-tipped nozzle (inner nozzle of Nozzle II) on P_{0i}/P_a and H/d

4.2 Coaxial jets from Nozzle I

Figure 5 shows the shadowgraphs of the co-axial free jets issuing from Nozzle I with a fixed value of $P_{0i}/P_a=5$ and several values of P_{0o}/P_a . It can be seen that the MSD observed in Fig. 3(b) almost disappears in Fig. 5(a) due to the presence of the outer annular jet. It is noted that a very small MSD exists in Fig. 5(a), since a slip line issues from the intersection of the incident shock wave. However, it can be seen clearly that the outer annular jet has favorable effects for reducing the diameter of MSD. Since the MSD is very small, the subsonic flow just downstream of MSD is accelerated to supersonic in a short distance. Therefore, in Fig. 5(a), a repetitive shock structure can be observed far downstream.

Figure 6 shows the Mach contour, the pressure contour and the shadowgraph of the co-axial jet with $P_{0i}/P_a=5$ and $P_{0o}/P_a=1.5$ obtained by the numerical simulation, and the calculated shadowgraph is compared with the actual one. The very good agreement between the calculated shadowgraph and the

(a) $P_{0o}/P_a = 1.5$ (b) $P_{0o}/P_a = 3$ (c) $P_{0o}/P_a = 5$ (d) $P_{0o}/P_a = 6$

Fig. 5 Shadowgraphs of coaxial free jets issuing from Nozzle I. with $P_{0i}/P_a=5$

Fig. 6 Mach contour, pressure contour and shadowgraph of coaxial jet issuing from Nozzle I with $P_{0i}=5$ and $P_{0o}/P_a=1.5$

actual one confirms the reliability of the numerical simulation. No shock waves are formed in the outer annular jet, since it is subsonic due to the low pressure ratio P_{00}/P_a . It can be seen from the Mach contour that an annular vortex region exists near the nozzle exit between the outer annular jet and inner jet. It is noted, however, that the Mach contour does not show the size of the vortex region. It can be observed from the streamlines (not shown in this paper) that the outer and inner jets join each other due to the Coanda effect, a short distance from the nozzle exit which is approximately $(D_i - d)/2$. The pressure contour shows that the pressure in the vortex region is below atmospheric pressure. However, an annular region where the pressure is higher than the atmospheric pressure is formed as the inner and outer jets collide with each other. The inner jet expands suddenly at the nozzle exit, emanating an expansion fan. A strong conical converging shock is also formed in the inner jet. It seems that the conical shock wave is built up slightly downstream of the nozzle exit. This shock cannot interact regularly at the axis, and a very small MSD is formed at the centerline. The presence of the small MSD can be confirmed, since the Mach number just downstream of the intersection is below unity. However, the MSD is very small compared with that observed in Fig. 3(b). It is thought that the presence of the high-pressure region described above causes this small MSD. It can be seen from the Mach contour and the pressure contour that a second conical converging shock wave (or compression wave) is formed from the high-pressure region. This shock wave is so weak that it cannot be seen in the shadowgraph.

Figure 7 shows the Mach contour, the pressure contour and the shadowgraphs of the coaxial jet with $P_{0i}/P_a=5$ and $P_{00}/P_a=3$. Figure 7(b) shows that the simulated shadowgraph does not coincide with the

Fig. 7 Mach contour, pressure contour and shadowgraph of coaxial jet issuing from Nozzle I with $P_{0i}/P_a=5$ and $P_{00}/P_a=3$

actual shadowgraph precisely. However, the qualitative agreement is fairly good. In this case also, the pressure in the annular vortex region is below atmospheric pressure, and a high-pressure region is formed downstream of the vortex. Therefore, the inner jet expands suddenly at the nozzle exit. Then, a conical converging shock wave which generates a small MSD at the jet center is formed slightly downstream of the nozzle exit. The annular jet is supersonic since $P_{00}/P_a=3$. Therefore, several annular shock cells are formed near the nozzle exit. The shock waves which compose the annular shock cells cannot intrude into the inner jet as long as the shear layer downstream of the annular vortex region is subsonic. However, as the shear layer is accelerated to supersonic, a conical diverging shock wave intrudes into the inner jet from the end of the third annular shock cell. Figure 5 shows that the annular shock cell becomes larger as P_{00}/P_a is raised further. In Figs. 5(c) and (d), only one annular shock cell can be observed clearly in each jet. However, the shock structure in the coaxial jet is quite complicated, since several converging conical shock waves intrude into the inner jet.

Figure 8 shows P_{jc} as a function of both H/d and P_{00}/P_a . It can be clearly observed that the presence of the outer annular jet can raise P_{jc} considerably in the range of $H/d > 3$. At $P_{00}/P_a=1.5$, P_{jc}/P_a shows large periodical variation which is depicted in Fig. 5(a).

Figure 9 shows the shadowgraphs of the coaxial free jets issuing from Nozzle I with a fixed value of $P_{0i}/P_a=9$ and several values of P_{00}/P_a . Comparing Fig. 9 with Fig. 3(d), it can be seen that the presence of the outer annular jet is favorable for reducing the diameter of MSD. Figure 9(c) shows that the first conical converging shock wave intersects almost regularly at the axis in the coaxial jet if $P_{00}/P_a=4$. Although the second conical converging shock wave forms a normal shock wave just downstream of the intersection point of the first conical shock wave, this normal shock wave seems very weak. Figure 10

Fig. 8 Dependence of P_{jc}/P_a generated by Nozzle I with $P_{0i}/P_a=5$ on H/d and P_{00}/P_a

shows P_{jc} as a function of both H/d and P_{00}/P_a . Large periodical variation in P_{jc}/P_a can be clearly observed at P_{00}/P_a around 4. Therefore, the use of an outer annular jet with appropriate P_{00}/P_a and H/d can create a considerably high P_j/P_a .

4.3 Coaxial jets from Nozzle II

Figure 11 shows the shadowgraphs of the coaxial free jets issuing from Nozzle II with a fixed value of $P_{0i}/P_a=5$ and several values of P_{00}/P_a . In this case

(a) $P_{00}/P_a = 1.5$ (b) $P_{00}/P_a = 3$ (c) $P_{00}/P_a = 4$ (d) $P_{00}/P_a = 7$

Fig. 9 Shadowgraphs of coaxial free jets issuing from Nozzle I with $P_{0i}/P_a=9$

Fig. 10 Dependence of P_{jc}/P_a generated by Nozzle I with $P_{0i}/P_a=9$ on H/d and P_{00}/P_a

(a) $P_{00}/P_a = 1.5$ (b) $P_{00}/P_a = 3$ (c) $P_{00}/P_a = 5$ (d) $P_{00}/P_a = 7$

Fig. 11 Shadowgraphs of coaxial free jets issuing from Nozzle II with $P_{0i}/P_a=5$

also, it can be clearly seen that the outer annular jet has favorable effects for reducing the diameter of MSD.

Figures 12 and 13 show the Mach contour, the pressure contour and the shadowgraphs of the coaxial jet with $P_{0i}/P_a=5$. The plenum pressure of the outer annular jet P_{00}/P_a is 1.5 in Fig. 12 and 3.0 in Fig. 13. It can be seen that the pressure in the annular vortex region in coaxial jets from Nozzle II is higher than the atmospheric pressure, since the outer annular jet impinges strongly on the inner jet. It seems that the first conical converging shock wave is formed along with an expansion fan just at the edge of the inner nozzle exit. The first conical shock waves shown in Figs. 12 and 13 intersect almost regularly at the jet centerline. The second conical shock wave is also created due to the collision of the inner and outer jets. It seems that each second conical shock wave in Figs. 12 and 13 forms a very small MSD. In Fig. 13, only one annular shock cell can be observed, since the Mach number in the outer annular jet is reduced

Fig. 12 Mach contour, pressure contour and shadowgraph of coaxial jet issuing from Nozzle II with $P_{0i}=5$ and $P_{00}/P_a=1.5$

Fig. 13 Mach contour, pressure contour and shadowgraph of coaxial jet issuing from Nozzle II with $P_{0i}=5$ and $P_{00}/P_a=3$

severely due to the strong collision with the inner jet.

Figure 14 shows P_{jc} as a function of both H/d and P_{00}/P_a . It can be seen that the periodic variation of P_{jc}/P_a with H/d at $P_{00}/P_a \approx 2$ in Fig. 14 is clearly larger than that in Fig. 8. This shows definitely that Nozzle II is more favorable for an assist jet than Nozzle I if P_{00}/P_a and H/d are chosen properly.

Figure 15 shows the shadowgraphs of impinging jets issuing from Nozzle II with $P_{0i}=5$ and $P_{00}/P_a=1.5$. Figure 15(a) shows that a large MSD is formed in the jet due to the effect of the impinged flat plate. It can be seen from Fig. 14 that such a large MSD causes severe reduction in P_{jc} . Figures 15(b)–(d) show that the effect of the impinged plate is restricted near the plate if H/d is larger. At $H/d=2.75$, no definite shock waves are observed near the impinged plate. Therefore, P_{jc} is high at $H/d=2.75$, as seen in Fig. 14. However, a plate shock wave is observed clearly at the expanded region of the jet in the case of $H/d=4$. Since the Mach number is relatively high in the expansion region, the reduction in stagnation pressure due to the plate shock wave is severe. Therefore, it is seen from Fig. 14 that the plate shock wave at the expanded region of the jet leads to the severe reduction in P_{jc} . On the other hand, the plate shock wave is located at the contracted region of the jet in the case of $H/d=4.25$ as shown in Fig. 15(d). It is seen from Fig. 14 that P_{jc} is relatively high at $H/d=4.25$.

Fig. 14 Dependence of P_{jc}/P_a generated by Nozzle II with $P_{0i}/P_a=5$ on H/d and P_{00}/P_a

Fig. 15 Shadowgraphs of coaxial impinging jets issuing from Nozzle II with $P_{0i}/P_a=5$ and $P_{00}/P_a=1.5$

The profiles of the surface pressure P_j measured at $P_{0i}/P_a=5$ and $P_{00}/P_a=1.5$ are shown in Fig. 16, where r is the radius with the jet axis at $r=0$. The profiles for $H/d=2.25$ and 4.00 show that the pressure near the nozzle axis is very low and rises to a maximum at $r/D \approx 0.9$. These profiles suggest the presence of a large vortex ring on the impinged plate⁽²⁾. The vortex ring is created, since the loss in the stagnation pressure at the central portion of the jet is severe due to the MSD and/or the plate shock wave. It is obvious that the gas accumulation at the central stagnation point is detrimental to the laser's cutting ability. It can be seen that the vortex ring does not disappear even at $H/d=2.5$ and 4.25. However, the vortex ring becomes very small and P_{jc} is raised significantly.

Figure 17 shows the shadowgraphs of the coaxial free jets issuing from Nozzle II with a fixed value of $P_{0i}/P_a=9$ and several values of P_{00}/P_a . It can be seen in Figs. 17(b)–(d) that the first conical shock wave intersects regularly. The second conical shock wave forms a MSD at the jet center. However, the diameter of the MSD seems smaller than that shown in

Fig. 16 Profiles of the surface pressure measured at $P_{0i}/P_a=5$ and $P_{00}/P_a=1.5$

(a) $P_{00}/P_a=1.5$ (b) $P_{00}/P_a=3$ (c) $P_{00}/P_a=5$ (d) $P_{00}/P_a=7$

Fig. 17 Shadowgraphs of coaxial free jets issuing from Nozzle II with $P_{0i}/P_a=9$

Fig. 18 Dependence of P_{jc}/P_a generated by Nozzle II with $P_{oi}/P_a=9$ on H/d and P_{00}/P_a

Fig. 3(d). Figure 18 shows P_{jc} as a function of both H/d and P_{00}/P_a . Large periodical variation in P_{jc}/P_a can be clearly observed at P_{00}/P_a around 3. However, the peak of P_{jc}/P_a is not very large compared to that shown in Fig. 14.

5. Conclusions

The present investigation on the underexpanded coaxial jets shows clearly that the presence of the outer annular jet has favorable effects for reducing the diameter of MSD which is formed in the inner jet. Within the range of the present investigation, the shadowgraphs and the numerical simulation show that the pressure in the annular vortex region which is formed in the co-axial jet issuing from Nozzle I is below atmospheric pressure. On the other hand, the corresponding pressure in the coaxial jet generated by Nozzle II is higher than atmospheric pressure. There-

fore, the shock structure in the coaxial jet depends strongly on the ejection angle of the outer annular nozzle. The shock structure also depends strongly on the combination of P_{00} and P_a . The present study shows definitely that Nozzle II can create higher P_{jc} than Nozzle I, if the combination of plenum pressures and H/d are chosen properly. However, the maximum P_{jc} obtained in the present study is lower than that produced previously by a simple annular jet⁽⁴⁾. This result shows that the simple annular jet is more favorable than the coaxial jet for laser cutting.

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