An Experimental Study of Underexpanded Moist Air Jet Impinging on a Flat Plate

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Abstract

When a gas expands through a convergent nozzle in which the ratio of the ambient to the stagnation pressures is higher than that of the critical one, the issuing jet from the nozzle is underexpanded. If a flat plate is placed normal to the jet at a certain distance from the nozzle, a detached shock wave is formed at a region between the nozzle exit and the plate. In general, supersonic moist air jet technologies with nonequilibrium condensation are very often applied to industrial manufacturing processes. In spite of the importance in major characteristics of the supersonic moist air jets impinging to a solid body, its qualitative characteristics can not even know.

In the present study, the effect of the nonequilibrium condensation on the underexpanded moist air jet impinging on a vertical flat plate is investigated experimentally. Flow visualization and impact pressure measurement are performed for various relative humidities and flat plate positions. The obtained results show the plate shock and Mach disk are dependent on the nozzle pressure ratio and the relative humidity, but for a given nozzle pressure ratio, the diameters of the plate shock and Mach disk depend on the stagnation relative humidity. The impact pressure deviation from the flow of without condensation is large, as the relative stagnation humidity increases.

Introduction

The free jet impinging on a solid surface can see in various fields, such as, in the problems of landing or take-off of a V/STOL with jet engine, jetted gas or steam from a nozzle into turbine blades, terrestrial rocket launch, jet for soot blower, thrust control system and so on[1].

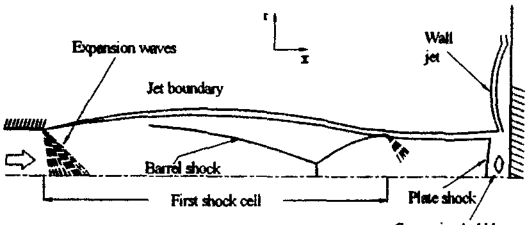


Fig. 1 Schematic diagram of impinging jet flow field

These impinging jet flow fields are generally seemed to be extremely complex. As shown in Figure 1, the supersonic jet impinging vertically on a flat plate is known as the flow that contains the mixed regions of subsonic and supersonic, interaction between shock and expansion waves and turbulent shear flow region. The structure of impinging jet is dependent on the design Mach number, that is, nozzle geometry, nozzle pressure ratio and the distance between nozzle exit and flat plate etc.[2,3]

Also, the characteristics of the supersonic impinging jet are related closely to shock wave system forming in the front of body[4].

On the other hand, such as in supersonic flow of an actual jet burner, a steam turbine cascade and various industrial jet technologies, condensable gas is used as working fluid[5,6]. In these cases, the nonequilibrium condensation is occurred at the region between nozzle exit and an object. In a supersonic flow with condensation, the surrounding gas will be heated by the release of latent heat of condensation. So, the jet flow with condensation is quite different from that without condensation.

That is, the structure of jet and the flow properties along the jet with condensation are quite different. But the study for the effect of nonequilibrium condensation on the wave structure of supersonic impinging jet, impact pressure on a solid body and so on were not so perfectly achieved till now.

In these connections, in the present study, the effect of the nonequilibrium condensation on the under-expanded jet in in-draft type supersonic wind tunnel is investigated experimentally by using of moist air as working fluid.

Experimental Setup and Method

In the in-draft type intermittent supersonic wind tunnel showing in Fig.2, the experiments for the supersonic impinging jet are performed. The apparatus consists of reservoir of $44m^3$, vacuum tank of $5m^3$ and vacuum pump, sonic nozzle, flat plate, pressure measuring system and schlieren system etc. The jet of a moist air as working fluid is generated by in-drafting of working fluid from the reservoir of standard atmospheric condition through an axisymmetric convergent nozzle. To measure the impact total pressure of the supersonic impinging jet on the vertical flat plate, as shown in Fig. 3, the pressure measurement holes of 0.8 mm diameter are arranged to 1mm interval from the center of the rectangular flat plate of 100 x 150mm to radial direction of jet, whose range of r/D_e is 1.6. The sensed pressure by pressure scanning valve is A/D converted, and then recorded at the PC.

During experiment, the supersonic jet of steady state can be attained when the distance between the vertical flat plate and nozzle exit should be kept more than dimensionless fixed one of x/D_e=0.6. Corresponding x=0 to the nozzle exit, the dimensionless measuring range from nozzle exit to the flat plate x_n/D_e is 5.2. To visualize impinging jet flow fields, a schlieren visualization system with a Xe light source of 1kW is adopted.

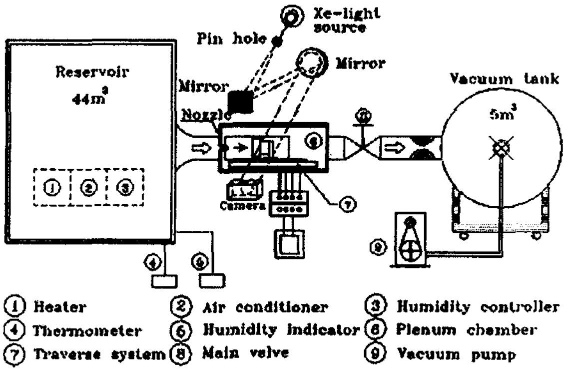
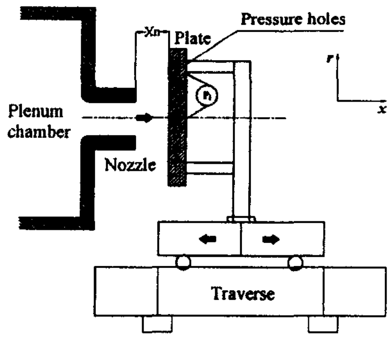
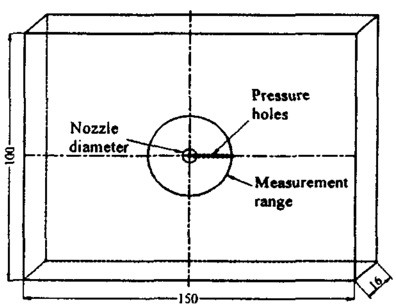


Fig. 2 Schematics of experimental apparatus



(a) Test rig



(b) Flat plate

Fig. 3 Test rig for jet impingement experiment

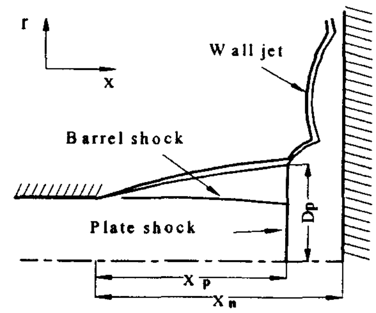
The flow visualization is taken with shadowgraph method, and the taken pictures are sent to the PC through the CCD camera. The stagnation condition having p_0=101kPa and T_0= 293K is kept constantly. And the relative humidity in the stagnation reservoir and the nozzle pressure ratio are varied in the ranges of 30-70% and p_0/p_b=4.7-7.5, respectively. Moreover, to obtain quantitative values for impinging jet structure, the method of a transparent ruler attached to the test window is used.

Results and Discussion

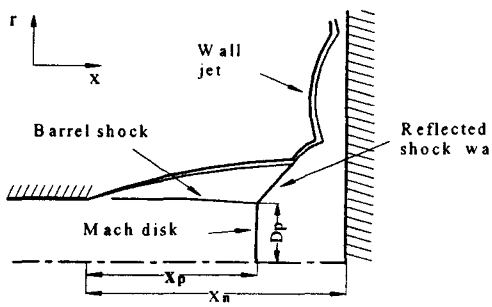
Visualization of flow field

Fig.4 shows the reflection patterns of barrel shock wave, technical terms and so on. In which, x_n and x_p are positions of flat plate and plate shock, respectively. D_p means the diameter of plate shock(or Mach disk). When a supersonic jet is freely discharged from axisymmetric nozzle, a shock wave with Mach disk is formed by the Mach reflection of barrel shock in the vicinity of jet centerline. And a vertical flat plate exists in the supersonic flow of the jet, there are two reflection cases of barrel shock. One is called as plate shock case which has nearly a normal reflected shock wave, the other is called as Mach disk case which has an oblique reflected shock wave.

In the present range of study, it is turned out that as the position of flat plate moves to the jet downstream, the reflection pattern of incident barrel shock is Mach disk case. If flat plate moves to jet downstream more, a new flow field with shock wave, which depends on the wave system of the first shock cell, is formed.



(a) Plate shock case



(b) Mach disk case

Fig. 4 Definition of reflection pattern of supersonic impinging jet at first shock cell

In such a case, the shock wave formed by existence of flat plate is called as the plate shock case.

Fig. 5 shows the results of visualized impinging jet flow field for the various positions of flat plate, in which the stagnation relative humidity φ_0 and a nozzle pressure ratio p_0/p_b are constants as 30% and 4.7, respectively. The plate shock case continues to the values of about 1.2 in x_n/D_e and then its reflection pattern changes as the Mach disk case, which continues to 2.0. At last, the structure of jet changes to two shock cell systems.

In the case of small x_n/D_e, the sonic jet issuing from a nozzle exit accelerated to a supersonic, and decelerates to a subsonic through the plate shock system in the front of flat plate. For intermediate values of 1.2-2.0 in x_n/D_e, the Mach disk is formed in the vicinity of center of the jet, and the structure of Mach disc case consisting of barrel shock, Mach stem and oblique reflected shock is appeared. Beyond the value of x_n/D_e=2.2, the Mach disk is no longer formed in the first shock cell. Because the Mach disk inducing severe pressure losses at the first shock cell is not formed, and due to its above explained results the jet flow is kept in supersonic with high stagnation pressure at second and third shock cell. The plate shock is generated at the second shock cell, and the plate shock is formed at the third shock cell for x_n/D_e=4.0

Fig. 6 represents the visualization pictures with the variations of pressure ratios for the constant stagnation relative humidity φ_0 of 30%.

Figure (a) is the visualization result for the nozzle pressure ratio of p_0/p_b=4.7. The Mach disk for x_n/D_e=1.8 is formed in first shock cell. From x_n/D_e=2.2, the Mach disk is not formed in first shock cell, but the plate shock appears at the second shock cell.

On the other hand, in the case of p_0/p_b=5.4 showing in figure (b), the Mach disk is formed in the first shock cell regardless of the position of flat plate. But the diameter of the Mach disk is decreased as flat plate moves downstream. If the flat plate approaches to x_n/D_e=3.0, the plate shock is formed in the second shock cell being accompanied by the generation of a small diameter (about 10% in size of nozzle exit diameter) of Mach disk in the first shock cell. The formation of plate shock in second shock cell can be explained as follows. In the case of p_0/p_b=5.4, because the diameter of the Mach disk formed in the first shock cell is small, the flow fraction through the Mach disk to the whole flow becomes small. As results, it is easier than that case of small x_n/D_e to accelerate the subsonic passed the Mach disk to supersonic by exchanging the momentum with the outer flow passed through the barrel and reflection shock. If the nozzle pressure ratio p_o/p_b is 6.2 or above, the barrel shock and jet boundary are extended more, and the large Mach disk is formed in the first shock cell. But as can know from the results, the plate shock in the cases of 6.2 and 7.5 in p_0/p_b is not formed in the second shock cell. As the flat plate moves downstream, the Mach number just before the Mach disk is low and the diameter of the Mach disk formed in the first shock cell is small.

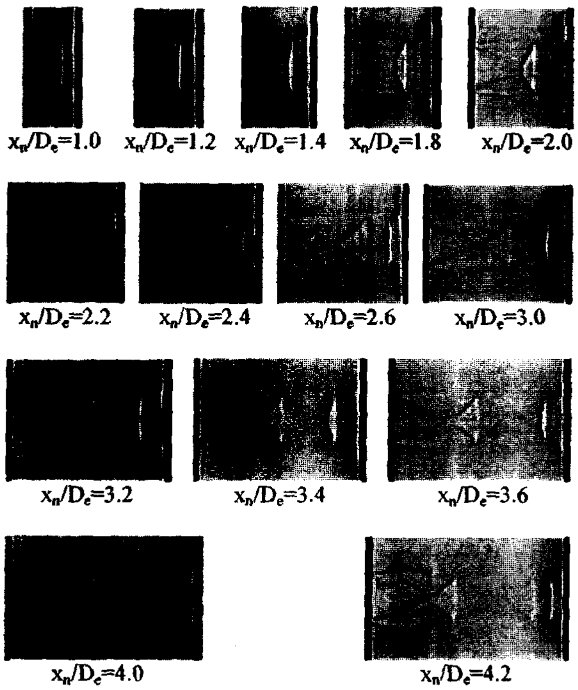


Fig. 5 Visualization pictures of impinging moist air jet (p_0/p_b=4.7, φ_0=30%)

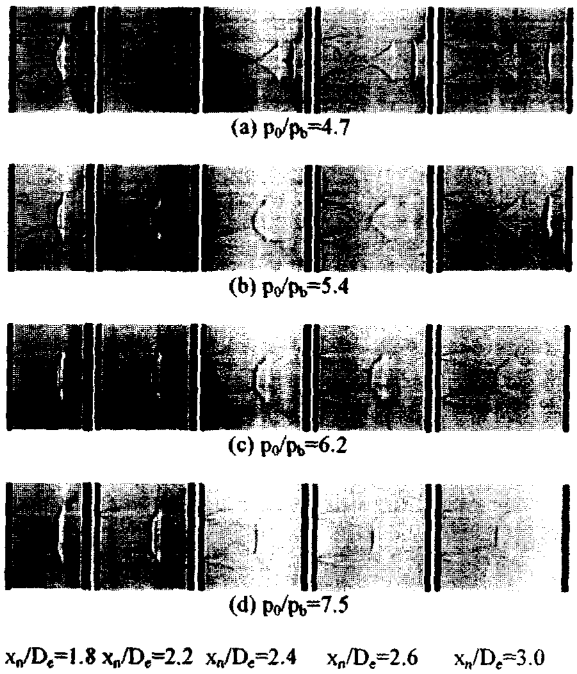


Fig. 6 Visualization pictures of impinging moist air jet (φ_0=30%)

Because the intensity and the diameter of Mach disk formed in the first shock cell increases with the increase of nozzle pressure ratio, the total pressure loss of the flow and the mass fraction through the Mach disk becomes large, which will result in no forming at the second shock cell.

For the same nozzle pressure ratio of 4.7, the taken visualization pictures of impinging jet are shown in Fig. 7 to investigate the effect of the relative humidity in the stagnation point on the structure of impinging jet. In case that flat plate is situated nearly to the nozzle exit, the impinging jet structure with the variation of relative humidity does not different with each other, but as flat plate moves downstream, the clear difference is shown. That is, in the cases beyond $x_n/D_e=1.4$, the larger φ_0 is, the diameter of the Mach disk increases, and the angle between the reflection shock and jet axis is larger. This is caused by that as the relative humidity is higher, the discharge amount of the latent heat by condensation increases.

On the other hand, it is turned out that the structures of jet for $x_n/D_e=2.2$ are same as those of free jets for the same stagnation conditions.

Fig. 8 shows the visualization pictures of impinging jet with the variations of stagnation relative humidity for the pressure ratio of $p_o/p_b=7.5$. Because the degree of underexpanded with respect to those cases of $p_o/p_b=4.7$, 5.4 and 6.2 is large, the diameters of plate shock and the Mach disk generated at the first shock cell are large, and the plate shock is not formed in the second shock cell. And the diameter of the plate shock increases with the increase of stagnation relative humidity for the same x.

The relation between the positions of plate shock(or Mach disk) and flat plate with the variations of stagnation relative humidity for $p_o/p_b=7.5$ is shown in Fig.9. In which x_p means the position of plate shock. As the flat plate moves to the downstream of jet, the position of Mach disk(or plate shock) moves also to downstream. Also, in the case of x_n/D_e =4.0 or above we can find that the position of plate shock(or Mach disk) is not influenced by the position of flat plate regardless of φ_0. This means that the Mach disk generated at the first shock cell is no longer influenced by the flat plate. And the position of plate shock(or Mach disk) is independent with φ_0, that is, we conclude that the position of plate shock or the Mach disk generated at the first shock cell depends on the position of flat plate but not depends on nonequilibrium condensation that occurs in jet.

The relation between the diameter of plate shock(or Mack disk) and the position of flat plate with the variations of stagnation relative humidity is shown in Fig. 10. Here D_p means the diameter of plate shock or the Mach disk. As the flat plate moves to the jet downstream from the initial position, the diameter of plate shock increases gradually because of underexpanded jet, shows the maximum at $x_n/D_e=1.5$, and then the diameter shows sudden drop at $x_n/D_e=2.2$ because the reflection pattern changes to Mach disk case as explained in Fig.4. From this, the diameter decreases gradually with the increase of distance between the nozzle exit and flat plate.

On the other hand, Because the larger stagnation relative humidity is, the release of latent heat by nonequilibrium condensation in supersonic becomes large, the diameter of plate shock or Mach disk is large with the increase of stagnation relative humidity for the same position of flat plate.

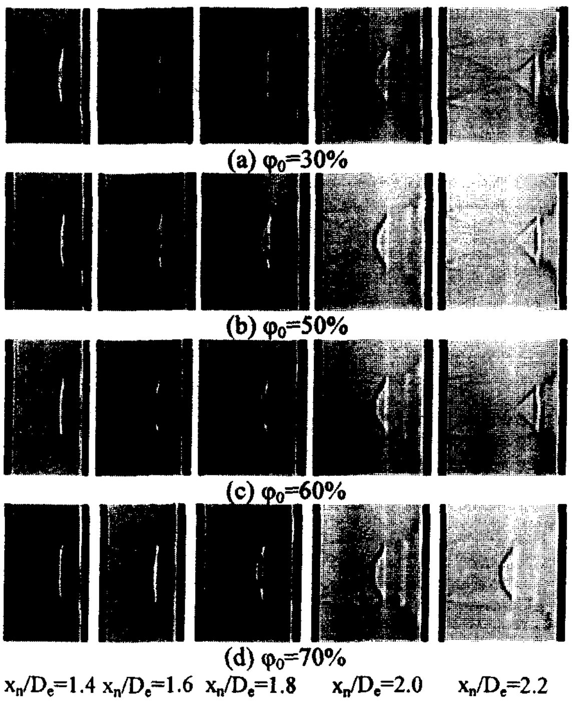


Fig. 7 Visualization pictures of impinging moist air jet ($p_o/p_b=4.7$)

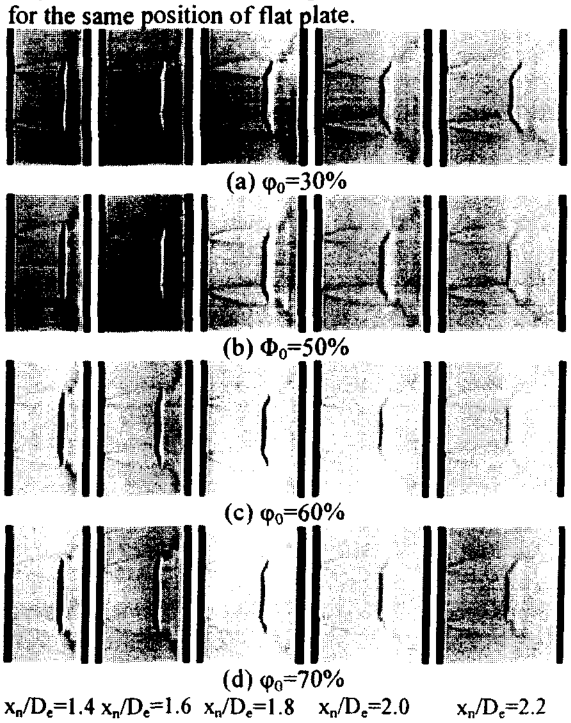


Fig. 8 Visualization pictures of impinging moist air jet ($p_o/p_b=7.5$)

Impact pressure distributions

Fig. 11 shows the impact pressure distributions at the jet axis with the variation of nozzle pressure ratio for φ_0=30%. In figure, symbol ● shows the result for p_0/p_b=4.7, the impact pressure decreases with the moving of the flat plate to the downstream of jet, it has the minimum at x_n/D_e=2.4, which is caused by the increase of Mach number(that is, the intensify of shock strength), and then it shows a sudden increase. This sudden increasing region of impact pressure corresponds to the just downstream region of Mach disk. After the impact pressure suddenly increases, it decreases monotonically, and then suddenly increases again in the vicinity of flat plate of x_n/D_e=3.6.

On the other hand, as the larger nozzle pressure ratio is, the smaller impact pressure becomes, and the position of sudden increment in impact pressure moves to the downstream and the increasing of impact pressure is smaller. The sudden increase of impact pressure can't see in p_0/p_b=7.5.

Fig. 12 shows the impact pressure distributions at the jet axis with the variation of φ_0 for p_0/p_b=6.2. In general, the impact pressure at the axis of jet decreases with the increase of stagnation relative humidity due to the release of latent heat by condensation to the surrounding flow of supersonic. Also, we can see that the patterns of impact pressure distribution for small φ_0 of 30-40% are same as that without condensation.

Conclusions

The obtained results for the study of underexpanded moist air jet impinging on a plate can be summarized as follows.

(1) The behavior of the plate shock and the Mach disk generated by placing of flat plate in supersonic moist air jet is dependent on the nozzle pressure ratio, relative humidity and location of flat plate.

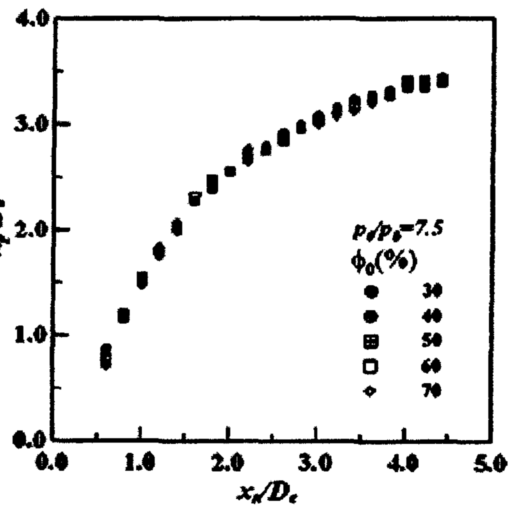


Fig. 9 Plate shock or Mach disk positions with x_n/D_e (p_0/p_b=7.5)

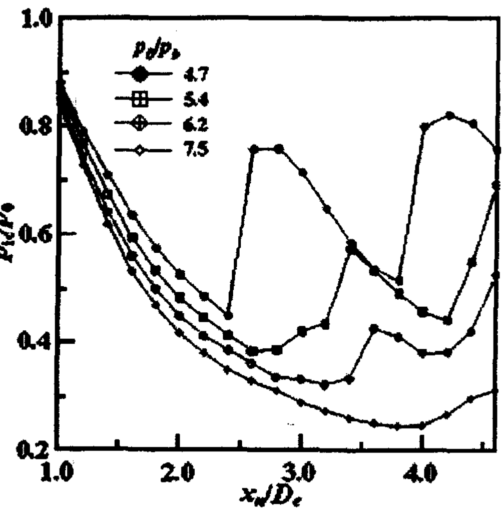


Fig. 11 Impact pressure at center of flat plate (φ_0=30%)

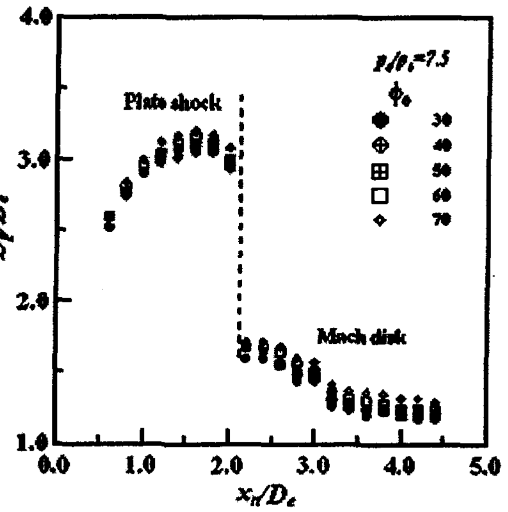


Fig. 10 Plate shock and Mach disk diameter vs x_n/D_e (p_0/p_b=7.5)

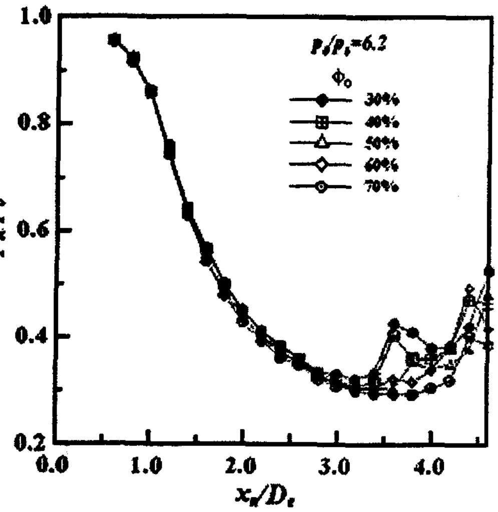


Fig. 12 Impact pressures at center of flat plate (p_0/p_b=6.2)

(2) As the relative humidity of the stagnation point increases, the diameters of plate shock and Mach disk and jet width for the same nozzle pressure ratio are increased, but the locations of those are not influenced.

(3) The higher the nozzle pressure ratio is, the impact pressure in the neighbor of jet becomes small.

Nomenclature

D_e	: nozzle exit diameter [mm]
D_p	: plate shock diameter [mm]
p_0	: stagnation pressure [Pa]
p_b	: back pressure [Pa]
p_e	: nozzle exit pressure [Pa]
p_i	: impact total pressure [Pa]
r	: radial distance [mm]
T_0	: stagnation temperature [K]
x_n	: location of flat plate from nozzle exit [mm]
x_p	: location of plate shock from nozzle exit [mm]
x,r	: cylindrical coordinate

Greek symbol

φ_0	: relative humidity [%]

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