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Study of Moderately Underexpanded Supersonic Moist Air Jets

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Supersonic moist air jet technologies are often applied to powerplants and industrial manufacturing processes, but the major features of supersonic moist air jets are not well known to date, including their qualitative characteristics. An experiment is performed to investigate relative humidity effects on underexpanded supersonic jet structures, such as Mach disk location and diameter, barrel shock wave, and jet boundary locations, etc. It is found that the Mach disk diameter and location are significantly influenced by the relative humidity of moist air. The Mach disk in underexpanded moist air jets is located farther upstream than in dry air jets, and the Mach disk diameter for moist air jets is smaller than that of dry air jets. The Mach disk diameter increases slightly as the relative humidity of moist air increases. Empirical equations are obtained for Mach disk diameter and location, as well as locations of the jet boundary and barrel shock, in underexpanded moist air jets.

Nomenclature

D_e = nozzle exit diameter
D_m = Mach disk diameter
p_b = backpressure
p_0 = stagnation pressure (atmospheric pressure)
R = nondimensional radius
r = radial distance
T_0 = stagnation temperature
x = axial distance from nozzle exit
x_m = location of Mach disk from nozzle exit
θ = angle
Φ_0 = initial relative humidity

Introduction

THE supersonic freejet has long received much interest from researchers because it has had many potential applications for the aeronautical and mechanical industries and has also been of importance in academic pursuits. Much effort has been devoted to the major characteristic features of supersonic jets.[1–3] According to these previous works, the underexpanded supersonic jet is specified by its barrel shock structure, Mach disk location, jet boundary configuration, velocity decay, and supersonic length, etc., which are usually determined by the jet pressure ratio.[4,5]

Much work has concentrated on the Mach disk because it is important in the determination of the major characteristics of supersonic jets.[6–8] The Mach disk is basically formed by the barrel shock wave reflections on the jet axis, and, thereby, the Mach disk is closely related to the barrel shock structure that can be, in turn, a strong function of the jet pressure ratio. It is well known that the Mach disk occurs when the jet pressure ratio is above a certain value.[6–8]

Meanwhile, additional work has been performed to investigate the effects of the working gas on supersonic jets.[9,10] The specific heat ratio of the working gas influences the jet pressure ratio, as well as the convective velocities of the gas particles. Recently, supersonic jets have been applied in powerplants and industrial manufacturing processes.[11,12] In these applications, the working gas is usually steam or moist air, which have not received the same level of attention in supersonic jet technologies as single-phase gases.

In general, rapid expansion of moist air or steam through a nozzle causes nonequilibrium condensation in the supersonic jet, which can be considerably affected by the latent heat released by the condensation of the moist components. This nonequilibrium condensation phenomenon is essentially an irreversible process leading to an appreciable entropy rise.[13,14] If the heat release due to the condensation exceeds a certain critical value, it is known that the nonequilibrium condensation leads to a discontinuous change in thermodynamic flow properties, called a diabatic shock wave.[13,14]

To the authors' knowledge, there are no previous reports to document the flow characteristics involved in supersonic moist air or steam jets. In the present study, an experimental facility has been fabricated to investigate supersonic moist air jets. A reservoir having a moisture generator provides the supersonic jets by means of a convergent nozzle. The reservoir maintains constant atmospheric pressure and temperature (stagnation conditions) throughout all of the tests, but the initial relative humidity of the moist air is varied to investigate supersonic moist air jets. The present study is the first investigation to explore humidity effects on supersonic moist air jet flows.

Experimental Facility and Method

A test rig for the supersonic moist air jet flow was fabricated, as shown schematically in Fig. 1. The upstream reservoir has a volume of 44 m^3, containing a heater, a thermometer, and a humidity controller. A convergent nozzle followed by a short straight section is installed on the exit of the inlet duct, which is connected to the upstream reservoir, and the nozzle exit diameter D_e is 5 mm. A plenum chamber is used to control the pressure level (backpressure p_b) at the nozzle exit, and it is connected to the inlet duct. The volume of the plenum chamber is designed to be sufficiently large so that it does not affect the jet flow. A control valve is installed between the plenum chamber and a vacuum tank with a volume of 5 m^3, and the control valve enables the pressure inside the plenum chamber to be adjusted so that the backpressure remains constant

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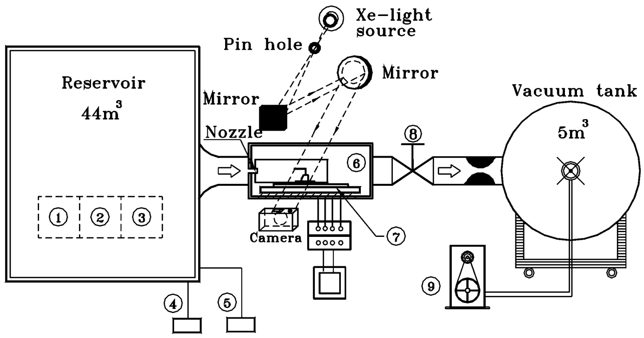


Fig. 1 Test rig for supersonic moist air jet experiment: 1, heater; 2, air conditioner; 3, humidity controller; 4, thermometer; 5, humidity indication; 6, plenum chamber; 7, traverse system; 8, valve regulator; and 9, vacuum pump.

during a test. This is done by means of a high-capacity vacuum pump, which is operated to provide the required pressure inside the plenum chamber during the tests. Careful attention was paid to prevent any appreciable disturbances from the vacuum pump propagating to the plenum chamber.

The plenum chamber has a pair of optical glass windows to allow visualization of the supersonic moist air jet flows. In the experiment, the pressure p_0 and temperature T_0 inside the upstream reservoir is held constant at atmospheric conditions, but the humidity is controlled using a moisture generator system so that the relative humidity of the moist air Φ_0 can be varied between 30 and 70%. The backpressure is also varied to obtain different values of the jet pressure ratio p_0/p_b. Several pressure transducers are installed on the wall surfaces of the plenum chamber to ensure that the jet pressure ratio remains constant.

During the tests, some flow unsteadiness of the supersonic moist air jet was found from flowfield visualizations; the Mach disk oscillated around a time-mean location for a given jet pressure ratio, but its amplitude was not so great that the flow unsteadiness significantly influenced the present experimental results. Unfortunately, the Mach disk oscillations could not be directly measured in the present study. A number of shadowgraphs were taken to extract the major characteristic features of the supersonic moist air jet flowfields. The pressure transducers were calibrated both statically and dynamically before each test. The uncertainty in pressure measurements is estimated to be less than ±1.5%. These estimations are based on the maximum possible fluctuations in the measurements. To quantify the major features of supersonic moist air jets, the Mach disk diameter and location, jet boundary, and barrel shock locations were obtained from shadowgraphs. The present study is the first investigation to explore humidity effects on supersonic moist air jet flows.

Results and Discussion

Typical shadowgraphs of underexpanded moist air jets are presented in Fig. 2, where the relative humidity Φ_0 of moist air is varied. For both of the pressure ratios applied, the jet is underexpanded at the exit of nozzle. The near-field structures of the supersonic moist air jets are clearly observed. It seems that the Mach disk location and diameter in the supersonic moist air jet are strong functions of the jet pressure ratio, but weak functions of the relative humidity of moist air. It is believed that the relative humidity of moist air does not remarkably change the macroscopic structures of the supersonic dry air jet, such as the barrel shock, Mach disk, jet boundary, etc. The diabatic shock wave due to the nonequilibrium condensation of moist air jet is not found in the present visualizations, though it appeared inside supersonic nozzles with the same relative humidity and stagnation conditions.[14] To quantify the relative humidity effect on the jet, quantitative data of the Mach disk location and diameter are collected from the visualization pictures.

Figure 3 shows the relative humidity effects on the Mach disk location and diameter. The upper curve in Fig. 3 indicates the empirical equations developed by Crist et al.[7] For the Mach disk location, the

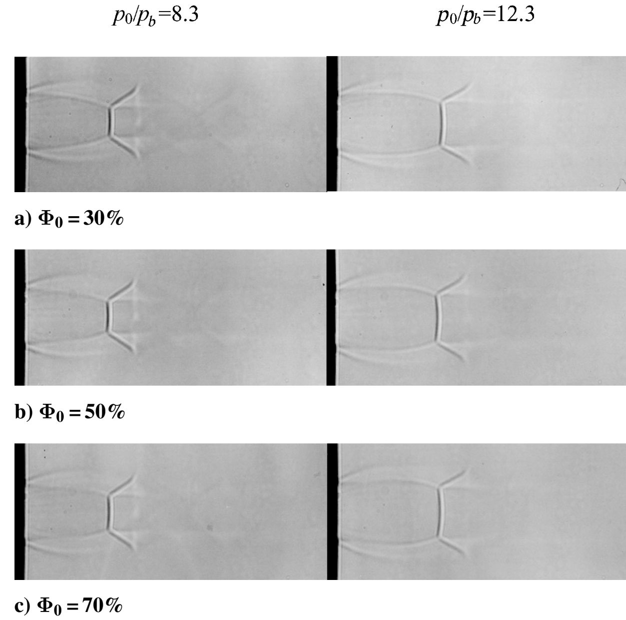
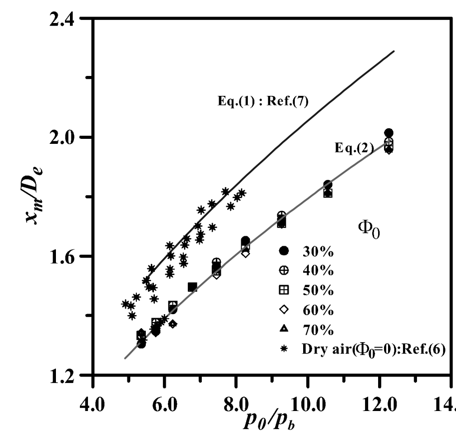
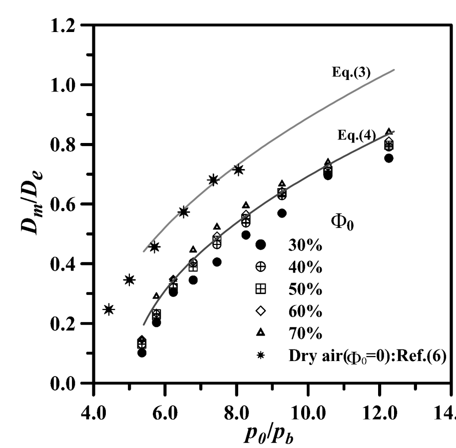


Fig. 2 Shadowgraphs of moderately underexpanded moist air jets.



a) Mach disk location



b) Mach disk diameter

Fig. 3 Mach disk location and diameter with different relative humidities.

empirical curve is given by

$$x_m/D_e = 0.65(p_0/p_b)^{\frac{1}{2}} \tag{1}$$

where x_m is the axial distance from the exit of the nozzle to the Mach disk. It is well known that Eq. (1) accurately predicts the Mach disk location in supersonic dry air jets. Note that all of the present moist air experimental data are significantly below the Mach disk location given by Eq. (1). It is likely that, for a given pressure ratio, nonequilibrium condensation of the moist air causes the Mach disk to move upstream as compared to dry air jets. The latent heat release due to the condensation will decrease the jet stagnation pressure of the underexpanded moist air jet. This may limit the expansion of the supersonic jet in the plenum chamber, and, thereby, the Mach disk in a moist air jet is located farther upstream than that in a dry air jet. In the present experiment, much effort has been paid to obtaining the experimental data for the dry air jet, but there was a limit in reducing the relative humidity of moist air in the upstream plenum chamber. The lowest relative humidity of moist air was about 30% in the present test rig because the atmospheric air had originally contained relative humidity over 50%.

It seems that, for the range of relative humidity of moist air applied in the present study, the variation in the relative humidity does not significantly influence the Mach disk location, even though there is some weak dependence of the Mach disk location on Φ_0, as shown in Fig. 3a. The present data show that the Mach disk locations in the supersonic moist air jet are empirically given by

$$x_m/D_e = 0.5673(p_0/p_b)^{\frac{1}{2}}, \qquad \text{for} \qquad 5.35 < p_0/p_b < 12.3 \tag{2}$$

where $30\% < \Phi_0 < 70\%$.

Meanwhile, Crist et al.[7] have argued that the Mach disk diameter in supersonic dry air jets depends on the nozzle configuration employed. They have suggested that the diameters of the Mach disk are given by Eqs. (3) and (4) for a convergent nozzle and a sharp-edged orifice, respectively (see Ref. 6):

$$D_m/D_e = 0.36(p_0/p_b - 3.9)^{\frac{1}{2}} \tag{3}$$

for a convergent nozzle and

$$D_m/D_e = 0.31(p_0/p_b - 5.0)^{\frac{1}{2}} \tag{4}$$

for a sharp edged orifice.

Figure 3b shows that the present moist air data agree well with Eq. (4) for dry air, even though the present experiment was carried out using a convergent nozzle followed by a straight section. For a given pressure ratio, the relative humidity of moist air apparently influences the Mach disk diameter; the higher the relative humidity is, the larger the Mach disk diameter is.

Therefore, the relative humidity of moist air changes the Mach disk diameter and location compared with dry air jets, and its variation has a more significant influence on the Mach disk diameter rather than the Mach disk location.

From the investigation of the relative humidity effect on the supersonic jet boundary, Fig. 4 shows the barrel shock wave and jet boundary configurations in the supersonic moist air jet for $p_0/p_b = 12.3$. The lines indicated are empirically given for a supersonic dry air jet.

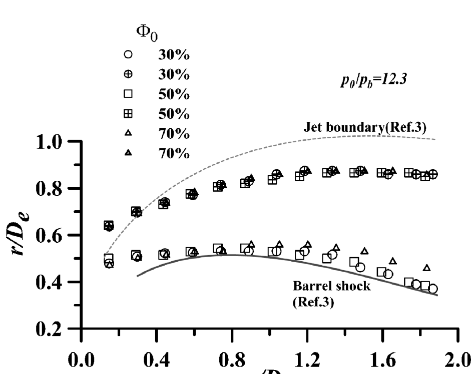


Fig. 4 Supersonic moist air jet boundary and barrel shock configurations ($p_0/p_b = 12.3$).

Assuming that an underexpanded jet discharged from a nozzle can be modeled by a source flow approximation, Kim and Shin[3] have derived the jet boundary and barrel shock configurations for a dry air jet, as given by Eqs. (5). The empirical curve of Eq. (5b) for dry air slightly underpredicts the barrel shock wave configuration for a moist air, whereas Eq. (5a) for dry air somewhat overpredicts the supersonic moist air jet boundary,

$$\theta_b = (1.87 - 0.00703 p_0/p_b) \cdot \exp\left\{-9.82(p_0/p_b)^{0.840} R\right\} \tag{5a}$$

barrel shock,

$$\theta_p = (1.90 - 0.00506 p_0/p_b) \cdot \exp\left\{-2.67(p_0/p_b)^{0.584} R\right\} \tag{5b}$$

where, for the barrel shock and jet boundary locations, x/D_e and r/D_e are obtained from $R\cos(\theta)$ and $R\sin(\theta)$, respectively. It is found that the barrel shock and jet boundary configurations of moist air jets are somewhat different from those of dry air jets, but for the range of the relative humidity applied in the present study, a variation in the relative humidity of moist air does not significantly affect the barrel shock and jet boundary configurations. The viscosity of moist air may be one of the factors to affect the present experimental results because it is different from that of dry air. The present data are not sufficient to quantify fully detailed relative humidity effects of the supersonic underexpanded jet flow. Further study is needed to make clear the nonequilibrium condensation effects on supersonic jet flows.

Conclusions

An experiment was performed to investigate relative humidity effects on underexpanded supersonic jet structures, such as Mach disk location and diameter, barrel shock wave, and jet boundary locations, etc. It was found that the Mach disk diameter and distance are influenced by the relative humidity of moist air. For a given pressure ratio, the Mach disk in the underexpanded moist air jets was located farther upstream than in dry air jets, and the Mach disk diameter for moist air jets was smaller than that of the dry air jets. The Mach disk diameter increased slightly as the relative humidity of moist air increased, but the Mach disk distance was not sensitive to the variation of the relative humidity. The barrel shock and jet boundary configurations were relatively less influenced by the relative humidity of moist air. From the present study, empirical equations were obtained for the Mach disk diameter and location, as well as the locations of the jet boundary and barrel shock in the underexpanded moist air jets. However, the present data are not sufficient to show the detailed mechanisms with regard to relative humidity effects on supersonic jets. Further study is necessary to validate the trends obtained in the present moist air jets.

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