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Geometrical Effects on the Near-Field Flow Structure of Coaxial Jets

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I. Introduction

COAXIAL jets have a wide range of applications and are used, for instance, in liquid propellant rocket engines, where a slow stream of liquid oxygen has to be mixed with a high-speed annular stream of gaseous hydrogen. When Reynolds numbers are high, the main parameter that governs the near-field development of the coaxial jets' flow is the ratio of the annular to the central jet momentum flux[1,2] $M = \rho_2 U_2^2/\rho_1 U_1^2$. This ratio reduces to the velocity ratio $r_u = U_2/U_1$ when the two streams are of equal densities. Depending on the value of r_u, the existence of two flow regimes has been demonstrated by Rehab et al.[1] The first one corresponds to the values of r_u in the range $1 < r_u < r_{uc}$ and is essentially characterized by the existence of a central potential core whose length is given by A/r_u, where A is a numerical constant. The other regime appears for $r_u > r_{uc}$, in which case the central potential core is chopped off and an unsteady recirculation bubble begins to form as shown in Ref. 2. It is to be expected that the numerical constant A and the threshold r_{uc} of the onset of the recirculating regime depend on initial conditions. These conditions are of two kinds: 1) the nozzle geometry, essentially characterized by the ratio of the outer to the inner nozzle diameters[3] $\beta = D_2/D_1$ and, possibly, the retraction of the inner nozzle with respect to the outer one, and 2) the exit conditions, i.e, the shape of the exit velocity profiles.[4] The Reynolds number, which fixes the mixing layer instability onset, acts only slightly on the inner core length provided it is large enough (10^4–10^5), which is generally the case in practice.[1] Dahm et al.[5] studied the case $r_u = 1$ in coaxial water jets with two different absolute values of the central and annular velocities. They showed the important effect of the wake behind the lip of the inner tube on the flow structure. In Ref. 1, it is shown that, when the velocity ratio is larger than unity, the inner mixing layer instability dominates the wake instability and the Reynolds number effect becomes very weak.

The present study focuses on the effects of the geometry of the coaxial injectors on the near-field flow structure. The dependence of the flow structure on the annular gap $e = (D_2 - D_1)/2$ is considered. The effect of the exit velocity profile is discussed. The consequences of a retraction of the inner tube on the coaxial jet flow dynamics is investigated too.

II. Experimental Setup and Methods

The experiments were conducted in a coaxial, axisymmetric water jet facility. The water is supplied by constant head tanks, and the jets issue into a large tank where water is at rest. Three coaxial nozzle configurations have been investigated. The long tube jet configuration is characterized by a fully turbulent pipe flow for the central jet and by a developed channel flow for the annular jet (at the nozzle exits). The diameter ratio is $\beta = 1.37$. The inner tube terminates, as is often the case in practical applications, with a divergence of a 6-deg angle and a lip thickness of 0.3 mm. The second configuration is similar to the first one but with the gap width increased; the diameter ratio is $\beta = 2.29$. In the third case, the jets emerge from convergent nozzles with contraction ratios of 2 and 4 for the central and the annular nozzles, respectively. The diameter ratio is $\beta = 1.35$.

The mean and fluctuation velocity measurements were made with constant-temperature, hot-film anemometers. The mean velocities at the nozzle exits are in the range $0 \leq U_1 \leq 1$ m/s and $0.3 \leq U_2 \leq 4$ m/s, giving Reynolds numbers on the order of 10^4–10^5. The measurement uncertainty for the velocity and the length scales [x_{p1} and $(x_{s2} - x_{s1})$] are 2.5 and 1%, respectively. For the critical velocity ratio, the uncertainty is approximately 5%.

III. Experimental Results

A. Effects of the Annular Gap Width

The mean axial velocity variations along the axis for different values of r_u have been measured, the outer velocity being fixed. The central jet potential core length x_{p1} is determined from the minimum in the mean velocity on the axis. In Fig. 1 the values of x_{p1} determined from the velocity minima are plotted as a function of r_u for the three geometries considered. It is observed that x_{p1} follows the relation $x_{p1}/D_1 = A/r_u$, with $-A$ a numerical constant equal to 6 for $\beta = 1.37$ and 7.5 for $\beta = 2.29$, so that for a given value of $r_u < r_{uc}$ the core length is longer when the gap is larger. Also, when the

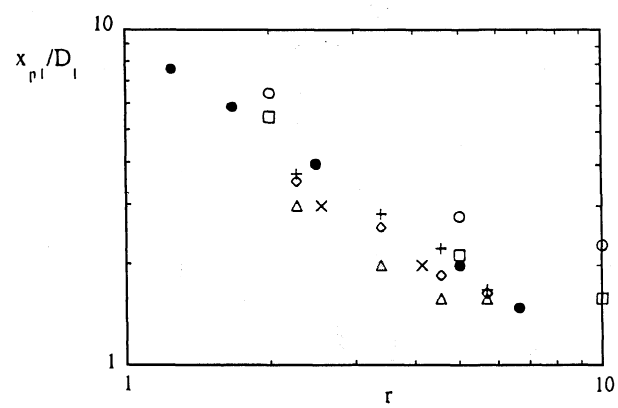

Fig. 1 Dependence of the central potential core on velocity ratio determined from the minima in axial velocity: Δ, $\beta = 1.37$; ◇, $\beta = 2.29$; and +, $\beta = 1.35$. Included for comparison: •, $\beta = 2$ (Au and Ko[6]); ×, $\beta = 1.4$ (Dahm et al.[5]); and □, $\beta = 1.51$ and 1.98 (Champagne and Wygnanski[3]).

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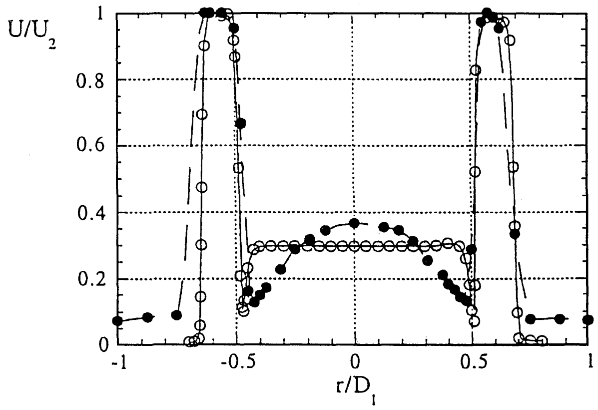

Fig. 2 Nozzle exit mean velocity profiles for $r_u = 3$ at $x = 2$ mm: •, $\beta = 1.37$ (inner tube with a divergent exit of 6 deg), and ○, $\beta = 1.35$ (convergent nozzles).

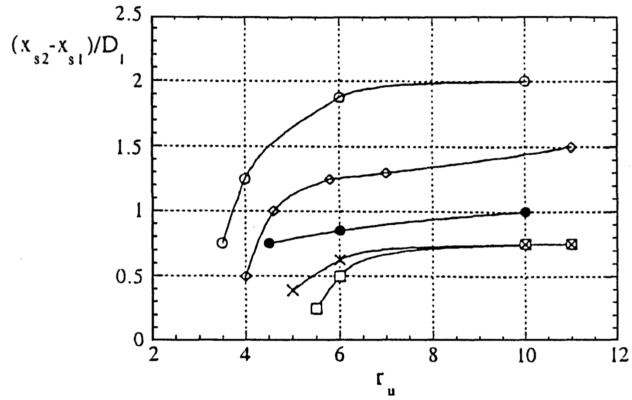

Fig. 3 Size of the recirculation bubble as a function of r_u: □, $L_R = 0$; ×, $L_R = 0.5D_1$; •, $L_R = D_1$; ◇, $L_R = 1.5D_1$; and ○, $L_R = 2D$. The points at $r_u = 11$ correspond to $r_u = \infty$.

nozzles are profiled, the potential core is somewhat longer. Au and Ko[6] found for $1.25 \leq r_u \leq 6.6$ and $\beta = 2$ the following dependence: $x_{p1}/D_1 \approx 9.9/r_u$. These authors ignore the mean velocity decrease along the axis due to the entrainment by the annular stream and consider the core as a uniform region that ends when the mean velocity U starts to increase with respect to U_1. This leads to an overestimation of the core length. The data of Champagne and Wygnanski[3] are also presented in Fig. 1 for the two values of $\beta = 1.51$ and 1.98. In their case, the inner core lengths are longer because their criterion is based on the peak in turbulent velocity intensities. This peak corresponds to the region where the annular jet merges on the axis, so that the inner core length is again overestimated; for $\beta = 1.98$, they find $x_{p1}/D_1 = 13/r_u$.

When r_u is larger than a critical value r_{uc}, the axial mean velocity has two local minima. This is indicative of a recirculation cavity, and the peak between the minima represents the absolute value of the backflow velocity.[1] The critical velocity ratio r_{uc} for the existence of a recirculation regime depends on β. The recirculation commences at $r_{uc} = 5.5$ for $\beta = 1.37$ and at $r_{uc} = 6.5$ for $\beta = 2.29$.

B. Effects of the Exit Velocity Profile

The results shown in Fig. 1 illustrate that, with the two geometries having the same relative annular gap $\beta = 1.35$ (profiled nozzle jets) and $\beta = 1.37$ (tube jets), the potential core lengths are different. In the two cases, the inner core length is represented by $x_{p1}/D_1 = A/r_u$, but A is larger in the case of convergent nozzles. It is equal to 8 for $\beta = 1.35$ and equal to 6 for $\beta = 1.37$. This result is explained by the fact that the presence of a divergence (6-deg angle divergence; see Sec. II) imposes on the flow an adverse pressure gradient that decelerates it at the center. The velocity profile is thus nearly parabolic at the exit of the divergent tube and has a top-hat shape at the exit of the convergent nozzle (Fig. 2). The ratio of the maximum center velocity to the bulk velocity $U_1/\bar{U}_1$ is then about 1.3 for $\beta = 1.37$ and 1 for $\beta = 1.35$. The reason is that, for a given velocity ratio r_u, the inner flow rate is 1.3 larger at the exit of the convergent nozzle and thus needs more surface to be entrained, hence a longer inner potential core. The exit velocity profile also affects the transition to the recirculating regime. The critical velocity ratio is found to be $r_{uc} \approx 8$ for $\beta = 1.35$ and 5.5 for $\beta = 1.37$.

IV. Retraction of the Inner Jet Nozzle

In this part, we are interested in the effects of a retraction of the inner injector relative to the external one by a certain distance L_R. This retraction length was varied from $0.5D_1$ to $2D_1$ for $\beta = 1.37$. In the following, the origin $x = 0$ always corresponds to the inner nozzle exit and the velocities U_1 and U_2 represent maximum inner and annular velocities measured at $x = 0$.

Axial mean velocity variations along the axis have been measured for moderate velocity ratios $1 < r_u < r_{uc}$ and for $L_R/D_1 = 0$, 0.5, 1, and 1.5. The location of the minimum of mean axial velocity, from which x_{p1} is determined, moves farther downstream as L_R increases. This is due mainly to the fact that the outer mixing layer starts to develop later, i.e., at $x = L_R$ downstream. Therefore, a retraction of the central nozzle is not just a simple translation of the flow upstream but leads, in fact, to a lengthening of the inner potential core.

The critical velocity ratios r_{uc} for different retraction lengths have been determined. Figure 3 shows the evolution of r_{uc} as a function of L_R. It is seen that, as L_R increases, r_{uc} decreases. To explain the evolution of r_{uc} with L_R, consider the following reasoning. The main mechanism governing the flow dynamics is the entrainment by the annular jet. This entrainment is linked with a radial pressure jump $\Delta P = \frac{1}{2}\rho u'^2$, where $u' = \alpha(U_2 - U_1)$ (with $\alpha \approx 0.17$ for the turbulent intensity within the mixing layer[7]). When there is a retraction of the inner tube ($L_R \neq 0$), there is an additional adverse pressure gradient whose origin is the wall shear stress τ_p at the external tube wall on a length equal to L_R. The pressure difference induced by the retraction is thus $\Delta P_R = (4L_R\tau_p)/D_2$, with $\tau_p = \frac{1}{2}\rho U_2^2 c_f$, where c_f is a coefficient of friction approximated to 7×10^{-3} for Reynolds numbers of 10^4–10^5 (see, for example, Ref. 8). Hence, the recirculation commences when the inner kinetic pressure $\frac{1}{2}\rho\bar{U}_1^2$ is not able to overcome the radial pressure jump $(\alpha^2/2)\rho(U_2 - U_1)^2$ increased by the adverse pressure difference due to the retraction: $\frac{1}{2}\rho\bar{U}_1^2 = (\alpha^2/2)\rho(U_2 - U_1)^2 + \Delta P_R$. Hence, we obtain

$$r_{uc} = \frac{1 + \{1 - (1 - \gamma)[1 + \sigma(L_R/D_1)]\}^{\frac{1}{2}}}{1 + \sigma(L_R/D_1)} \tag{1}$$

where $\gamma = (1/a^2\alpha^2)$ and $\sigma = (4c_f/\alpha^2\beta)$, with $a = U_1/\bar{U}_1$ and $\beta = D_2/D_1$. Equation (1) is in good agreement with the measured values of r_{uc} for different retraction lengths ($r_{uc} = 5.5$, 5, 4.5, 4, and 3.5 for $L_R/D_1 = 0$, 0.5, 1, 1.5, and 2, respectively). Equation (1) needs to be compared with other experimental results to know its limitations.

The backflow cavity that forms when $r_u > r_{uc}$ is delimited by two stagnation points. We define the size of the bubble as the distance on the axis between the two minima in mean velocity that correspond to the upstream (x_{s1}) and downstream (x_{s2}) stagnation points. The bubble size $(x_{s2} - x_{s1})/D_1$ is represented in Fig. 3 as a function of r_u. First, we remark that for a given L_R the cavity size increases with r_u until a maximum is reached when $r_u = \infty$. A strong dependence of the bubble size on L_R is observed. For instance, for $r_u = 10$, $x_{s2} - x_{s1} \approx D_1$ for $L_R = D_1$ and reaches $2D_1$ for $L_R = 2D_1$. Owen[9] has noticed in coaxial air jets that both the recirculation zone and the backflow intensity are more pronounced if the flow is confined by an external wall.

V. Conclusions

The coaxial jet flow structure and its dependence on nozzle geometries and initial conditions has been investigated for $r_u > 1$. The three effects studied are the gap width, the exit velocity profile, and the retraction of the inner nozzle. It is observed that, when the gap width $e = (D_2 - D_1)/2$ is increased, the inner potential core is longer and the transition to a recirculating regime occurs at higher values of r_u. The main reason for this is that the entrainment rate of the inner slow fluid by the fast annular stream is less important when the gap width is large. It is found that, as the ratio $U_1/\bar{U}_1$ increases, the inner potential core length gets shorter and the recirculation sets in earlier. It is also demonstrated that a retraction of the inner injector by a distance L_R not only has a translation effect but also increases somewhat the core length and causes a transition to a recirculation regime at lower values of r_u. It is the friction at the outer injector wall, over the retraction length, although weak, that reduces the critical velocity ratio.

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Origin of Streamwise Vortices in Supersonic Jets

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Introduction

THE purpose of this study was to clarify the initial conditions necessary for the development of streamwise vortices observed in underexpanded jets.[1–4] In particular, we examined whether the Taylor–Görtler instability established in the curved shear layers of an underexpanded jet was a sufficient condition for the formation of streamwise vortices. Recent work by Arnette et al.[4] indicates that strong streamwise structures develop in underexpanded jets issuing from nozzles having no noticeable surface imperfections. To the contrary, experiments performed by Novopashin and Perepelkin[2] suggest that a necessary condition for the formation of streamwise structures is a critical roughness on the nozzle surface. We addressed this point by examining supersonic jets using controlled disturbances with and without the presence of curvature. We expect that streamwise vortices will enhance the radial transport between the jet and the surrounding fluid. Understanding this most fundamental problem will have important technological impact on applications ranging from high-speed combustion to jet noise suppression.

Several studies have reported the presence of stationary streamwise vortices in the mixing-layer region of underexpanded axisymmetric jets.[1–4] Zapryagaev and Solotchin[1] examined the azimuthal total pressure variations in a Mach 1.5 conical nozzle at a pressure ratio of 10. Their measurements revealed the presence of stationary streamwise structure in the jet mixing region between the intercept shock and the jet boundary, resulting in pressure undulations around the jet periphery that exceeded 20 psi (138 kPa). They concluded that the streamwise vortices were set up in the highly curved shear layer due to an instability of the Taylor–Görtler type. Novopashin and Perepelkin[2] described a petal structure as seen in the shear layers of underexpanded jets issuing from a conical orifice. One principal finding of the research was that the petals were anchored to disturbances within the nozzle. Scratches in the orifice near the exit as small as 5 μm could be identified with azimuthal density variations in the jet downstream. It was observed that a critical nozzle surface roughness was necessary for spatial amplification leading to measurable streamwise structure in the jet shear layers. No streamwise structures were observed when the nozzle was sufficiently clean.

Krothapalli et al.[3] demonstrated that stationary streamwise structures are not limited to highly underexpanded jets, indicating that strong shear layer curvature is not a prerequisite for the phenomenon. Similar to the measurements of Zapryagaev and Solotchin[1] made at much higher pressure ratios, they documented total pressure variations on the order of 20 psi. More recent studies by King et al.[5] and Island et al.[6] indicate that fine surface imperfections are responsible for exciting streamwise structures in ideally expanded flows. However, an investigation by Arnette et al.[4] covering a wide range of operating conditions and nozzle types observed stationary streamwise structure in underexpanded jets but did not report any organized three-dimensionality at overexpanded or ideally expanded conditions. They concluded that the azimuthal variations were associated with streamwise counter-rotating vortex pairs that were amplified by a Taylor–Görtler instability in the curved shear layer, similar to the mechanism proposed earlier by Zapryagaev and Solotchin. Furthermore, the nozzles were described as free of imperfections, and hence no correlation was found between the shear layer dynamics and disturbances in the nozzle itself.

Results and Discussion

The present measurements were made in a blowdown jet facility having a total storage volume of 9.5 m^3 and supplied with compressed air at 140 bar. The experiments conducted at underexpanded flow conditions were performed using a fifth-order polynomial convergent nozzle having an exit diameter of 22.6 mm. Ideally expanded flow conditions were examined using a nozzle designed with the method of characteristics for flow at Mach 1.8 and having an exit diameter of 27.1 mm. A quantitative measure of the streamwise structure in the jet was made using a total head probe mounted on a computer-controlled, three-dimensional traversing system. Pressure data at each azimuthal station were averaged over a period of 0.6 s and collected in 2-deg increments. Estimates of the uncertainty in pressure were evaluated using precision error based on timewise measurements and the bias error of the Validyne pressure transducer and 16-bit analog-to-digital converter. Uncertainties in pressures were estimated at ± 0.5 psig, which corresponds roughly to the size of the symbols used in the figures. Further details of the facility can be found in Ref. 7.

Anticipating that strong streamwise structure would be more likely observed in an underexpanded jet, we started our investigation in the convergent nozzle operated at a pressure ratio of 5.1. Azimuthal pressure profiles taken at the axial locations of $x/D = 1.7$ and 2.5 are shown in Fig. 1, where D is the nozzle exit diameter. Small pressure undulations having peak-to-peak amplitudes from 2 to 5 psi can be observed around the entire jet periphery. These variations could be reproduced precisely between runs taken over a

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