[4]Haase, W., Brandsma, F., Elsholz, E., Leschziner, M., and Schwamborn, D., "EUROVAL–An European Initiative on Validation of CFD Codes," *Notes on Numerical Fluid Mechanics*, Vol. 42, Vieweg Verlag, 1993, Chap. 5.

[5]Hussain, A. K. M. F., and Reynolds, W. C., "Measurements in Fully Developed Turbulent Channel Flow," *Journal of Fluids Engineering*, Vol. 97, No. 4, 1975, pp. 568–580.

[6]Cantwell, B., and Coles, D., "An Experimental Study of Entrainment and Transport in the Turbulent Near Wake of a Circular Cylinder," *Journal of Fluid Mechanics*, Vol. 136, Nov. 1983, pp. 321–374.

[7]Ha Minh, H., Viegas, J. R., Rubesin, M. W., Vandromme, D. D., and Spalart, P., "Physical Analysis and Second-Order Modeling of an Unsteady Turbulent Flow: The Oscillating Boundary Layer on a Flat Plate," *Proceedings of the 7th Turbulent Shear Flow Symposium* (Stanford, CA), Paper 11-5, Aug. 1989.

[8]Chassaing, P., "Turbulence en Mécanique des Fluides," Institut National Polytechnique, Toulouse, France, Oct. 1990.

[9]Braza, M., and Nogès, P., "Numerical Simulation and Modeling of the Transition Past a Rectangular Afterbody," *Proceedings of the 8th Turbulent Shear Flow Symposium* (Munich, Germany), Paper I-2, 1991.

[10]Franke, R., and Rodi, W., "Calculation of Vortex Shedding Past a Square Cylinder with Various Turbulence Models," *Proceedings of the 8th Turbulent Shear Flows Symposium* (Munich, Germany), Paper 20-2, 1991.

[11]Patel, V. C., Rodi, W., and Scheuerer, G., "Turbulence Models for Near-Wall and Low Reynolds Number Flows: A Review," *AIAA Journal*, Vol. 23, No. 9, 1985, pp. 1308–1319.

[12]Braza, M., Jin, G., and Chassing, P., "Etude Numérique de Certains Phénomènes de Transition dans le Sillage de Profils d'Aile en Conditions Naturelles et Forçées," *Actes du Colloque de Mécanique des Fluides Numérique de Toulouse*, Institut de Méchanique des Fluides de Toulouse, Toulouse, France, 1993, pp. 16-1, 16-4.

[13]Kato, M., and Launder, B. E., "The Modelling of Turbulent Flow Around Stationary and Vibrating Square Cylinders," *Proceedings of the 9th Symposium on Turbulent Shear Flows* (Kyoto Univ., Japan), Paper 10-4, 1993.

[14]Jin, G., and Braza, M., "A Non-Reflecting Outlet Boundary Condition for Incompressible Unsteady Navier-Stokes Calculations," *Journal of Computational Physics*, Vol. 107, No. 2, 1993, pp. 239–253.

[15]Miley, S. J., "A Catalog of Low Reynolds Number Airfoil Data for Wind Turbine Applications," Dept. of Aerospace Engineering, Texas A&M Univ., Rept. DE82-021712, College Station, TX, Feb. 1982.

[16]Michos, A., Bergeles, G., and Athanassiades, A., "Aerodynamic Characteristics of a NACA 0012 Airfoil in Relation to Wind Generators," *Wind Engineering*, Vol. 7, No. 4, 1983, pp. 247–262.

Experimental Investigation of High-Speed Twin Jets

Gamal H. Moustafa*
Menoufia University, Shbien El-Kom, Egypt

Introduction

TWIN jets have been used in many engineering applications. Recently, the development of high-performance aircraft, in which high-speed twin jets are used, is a subject that has received increasing attention. Low-speed twin jets have been investigated extensively, and sufficient data on them are available for many practical engineering purposes.[1,2] Most of the work has been performed in incompressible turbulent jets. However, there have been very few studies of high-speed twin jets. The acoustic and screech phenomena of high-speed twin jets are the aim of most earlier investigators. Miller and Comings[3] studied the subsonic twin jet at only one nozzle spacing. They found that the region of subatmospheric static pressure between the converging jets accounted for their convergence and for the reversal of a considerable fraction of the total flow at the centerline against a strong downstream force of turbulent shear. The phenomenon of supersonic twin jet resonance was defined and studied by Seiner et al.[4] The effect of nozzle spacing on the coupled interaction of supersonic twin jets was examined by Wlezien.[5] He found that, for closely spaced nozzles, coupling occurred at low Mach numbers and was suppressed at high Mach numbers.

The main parameters governing the flowfield of a high-speed twin freejet are stagnation/ambient pressure ratio (p_0/p_a) and nozzle spacing S. The interaction between the jet and ambient fluid with varying these parameters just discussed is especially important in many engineering fields. The purpose of the present investigation is to study the effect of the parameters on the twin jet structure, development, and propagation. Only the mean flowfield is highlighted in this investigation.

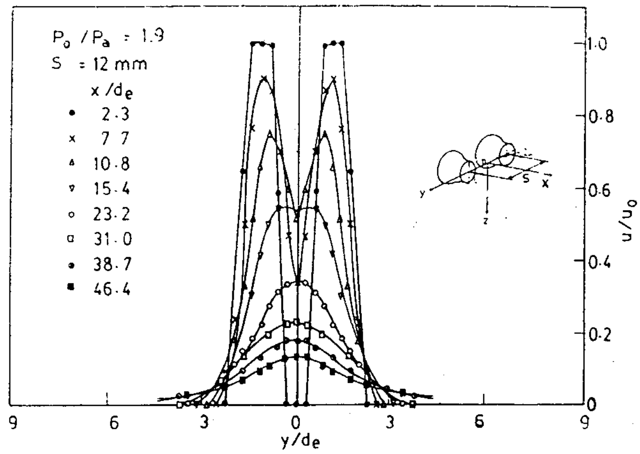

Fig. 1a Mean velocity profile.

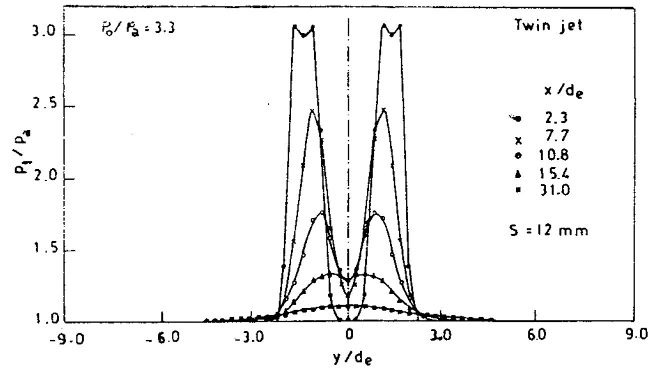

Fig. 1b Total pressure profiles of underexpanded jets.

Experimental Apparatus and Procedure

A blowdown high-pressure supply system was used to provide the airflow to a settling chamber. Before reaching the nozzle, air was passed through three mesh screens set 3 cm apart to reduce disturbances at the nozzle inlet. Two axisymmetric convergent nozzles having an exit diameter d_e of 4.2 mm set in a common wall were used. The spacing between the two nozzles was chosen as 12, 16, 18, and 22 mm. The stagnation/ambient pressure ratio was varied from 1.13 to 4. The Reynolds number based on d_e was varied from 4.2×10^4 to 1.3×10^5. Measurements of total pressure were made across the jet at several downstream locations using a pitot tube with an inside diameter of 0.5 mm. The distance between the nozzle centerline and the nearest wall was about 3 m so that wall effects were negligible in the experiments. The stagnation pressure was maintained at the desired value within an accuracy of $\pm 1.7\%$. The total pressure (pitot tube reading) measured in the jet (p_t) was uniform within $\pm 0.6\%$. The stagnation temperature was uniform at $35 \pm 1°C$ during the experiments.

Received Oct. 28, 1992; revision received May 20, 1993; accepted for publication Aug. 10, 1993.

*Lecturer, Department of Power Mechanical Engineering, College of Engineering and Technology.

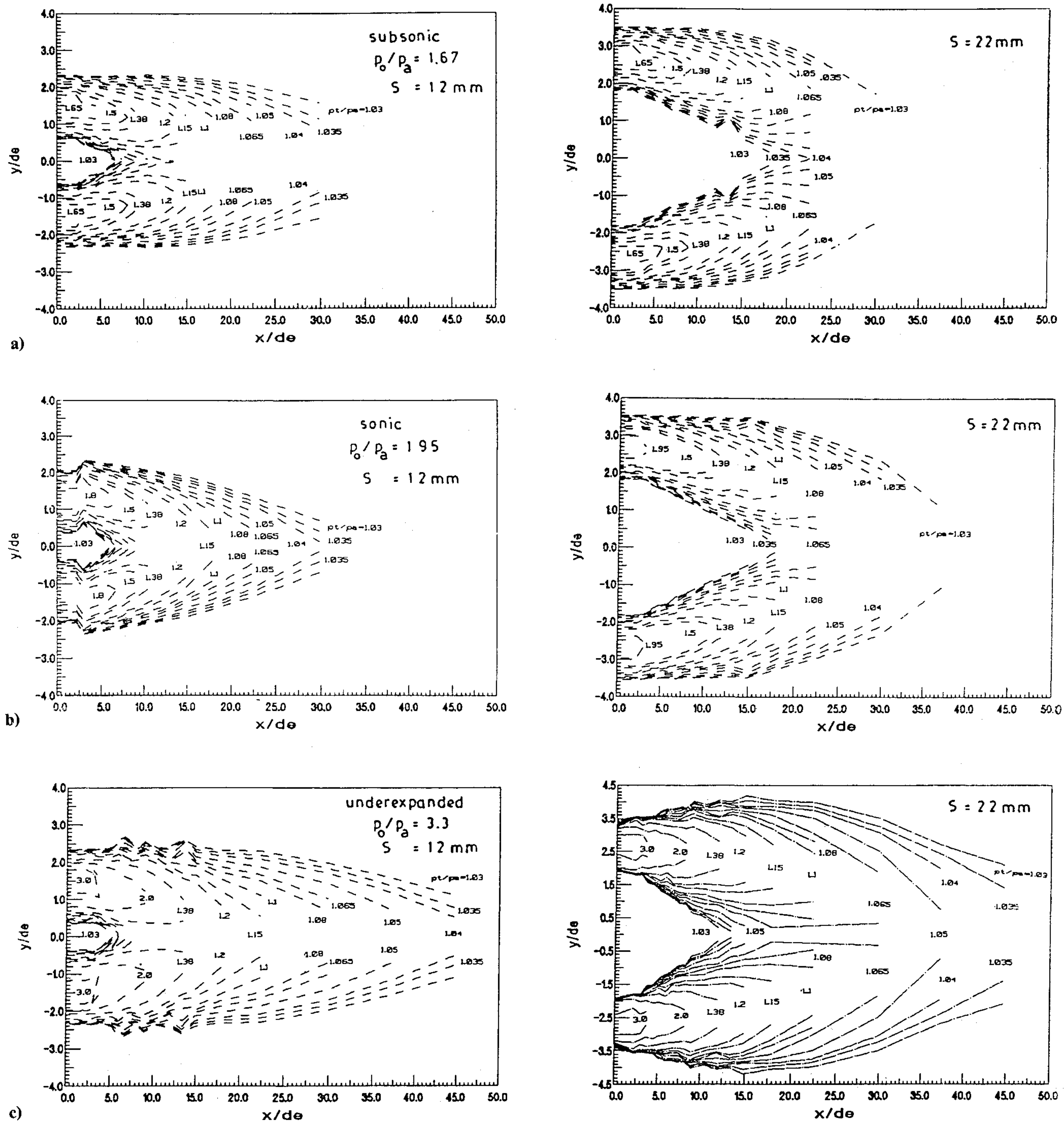

Fig. 2 Total pressure contours of the twin jet.

Results and Discussion

Figure 1a shows the mean velocity (u/u_0) profiles in the x-y plane at p_0/p_a = 1.9. The total pressure profiles of the underexpanded jet (p_0/p_a = 3.3) are given in Fig. 1b. In fact, the results from a total pressure probe cannot be converted directly into velocity or Mach number for the underexpanded jet because of the unknown entropy increase that has occurred in the core region. This is due to the shock waves associated with supersonic flows. In this case, the pressure distributions are more meaningful than the calculated velocity profiles.

In the region close to the nozzles (converging region), the main behavior of each jet is quite similar to that of a single jet. For instance, the centerline region of the mean velocity profile of each jet in this region is nearly flat. The flat portion disappears as the jets decay downstream. The maximum velocity/total pressure decreases and the jet width increases with distance from the nozzle exit. The two jets interact and approach the plane of symmetry as the distance from the nozzle exit increases. The jets intermix in the merging region where the velocity/total pressure in the plane of symmetry increases from zero at the merging point until it reaches a maximum just upstream of the point where the two jets join to form a single jet. The jet interaction begins at a distance between $4d_e$ and $9d_e$ and the combining (the beginning of combining region) occurs at a distance of $23d_e$ for S = 12 mm and at a distance of $30d_e$ for higher values of S. The location of the peak velocity/total pressure (u_{max}/p_{max}) shifts from the nozzle axis to the plane of symmetry as the distance increases downstream. The combined jet propagates as a single jet in the far region, and the "fully developed" behavior takes place as in the case of incompressible jets.

The underexpanded twin jet (Fig. 1b) exhibits many of the aforementioned features. The distinct centerline deficit in the core region of the underexpanded jet is related to the upstream Mach

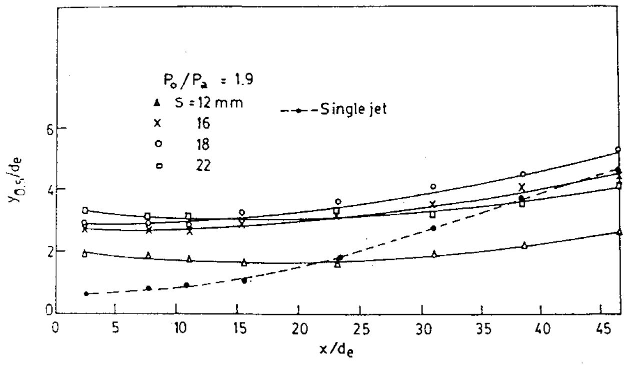

Fig. 3a Spread rate at different spacing between the two nozzles.

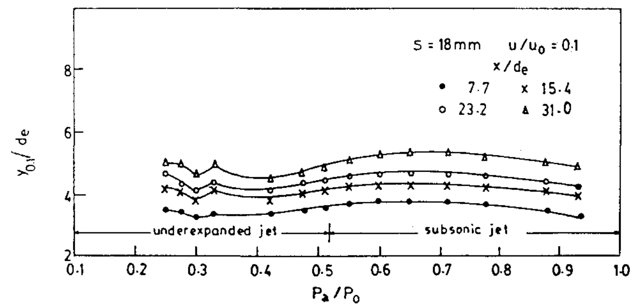

Fig. 3b Variation of jet width ($y_{0.1}$) with pressure ratio.

disk. This is the main difference between the underexpanded jet and the subsonic and sonic jets. Far downstream, the flow becomes subsonic and the fully developed flow behavior similar to that of a low-speed jet is observed.

Figure 2 shows the total pressure contours for different pressure ratios. The effect of nozzle spacing is also included in this figure. The behavior of the twin jet is quite similar at different pressure ratios and nozzle spacings. The three regions defined earlier are clearly observed, and the nozzle spacing has a strong influence on the starting point of these regions.

For lower values of nozzle spacing, the two jets mix and combine to form a single jet that is faster and very close to the nozzle exit. This process occurs farther from the nozzle exit plane with increasing S. Also, for smaller S, the jet axes undergo only a slight bending toward each other. However, in the case of higher nozzle spacings, the attraction force between them becomes more (due to larger entrainment), and therefore the bending of the jet axis becomes severe as seen for S = 22 mm. This, in fact, has strong effects on the core length, which becomes shorter than that of a single jet. Also, the jet bending brings down the spread rate of the twin jet as compared with that of a single jet.

For the subsonic and sonic jets, the pressure contours are quite similar. However, there are many differences between the pressure contours of the subsonic/sonic jets and those of the underexpanded jet. The effect of shock waves on the contours is seen in the core region of the underexpanded jet (shown as oscillating patterns). Also, the propagation distance of the underexpanded jet is longer. A more interesting fact is that the bending alters the shock cell structure. Therefore, the structure of the shock cell in the underexpanded jet is strongly affected by nozzle spacing (Fig. 2c). Far downstream, the pressure contours of the combined jet show the behavior of a single jet. However, the width of the underexpanded jet is larger than those of the subsonic and sonic jets. The large spread rate of the underexpanded jet is related to the interaction between the shock waves and the jet shear layer in the near field and the large amount of entrainment in the far field. It may be noted here that because of the lack of pitot tube data, the interpolation procedure failed to produce proper pressure contours at the centerline for some of the total pressure values.

The jet growth (spreading ratio) is commonly measured by the variation of the jet half-width. This is the distance between the plane of symmetry to the point in the y direction where the axial velocity becomes half of its maximum value at the particular axial location (x/d_e). Figure 3a shows the variation of the half-width $y_{0.5}/d_e$ with x/d_e for different S. The spreading ratio of a single jet is also given for comparison. The spreading ratio of the twin jet decreases slightly in the near field and then increases with increasing downstream distance. For $x/d_e \leq 15$, the spreading ratio of the twin jet is larger than that of the single jet for all cases of S. For $x/d_e >$ 15, the slope of the single jet half-width is higher than that of the twin jet. This can be understood, considering the facts that the entrainment of the ambient air is prevented in the inner region between the jets and also the jets bend toward each other. For large nozzle spacings (S = 22 mm), the lower spread rate is related to the excessive bending of the jet axes as well as the streaming effect of the ambient entrainment.

The variations of the jet width (defined as the $y_{0.1}$ distance at which $u/u_0 = 0.1$) are shown in Fig. 3b. The pressure ratio has been represented by p_a/p_0 in the figure. The jet width attains a maximum for some value of p_a/p_0 in the subsonic flow regime and then decreases near the sonic pressure ratio. At all axial distances, the variation in the jet width with pressure ratio is more or less similar and the peak value of the jet width occurs around $p_a/p_0 = 0.6$. For the underexpanded jet, the trend of the jet width with the variation of pressure ratio does not exhibit a fixed behavior. It decreases after the sonic flow value up to $p_a/p_0 = 0.42$ and then oscillates due to the shock cell patterns. This variation of the spread rate with pressure ratio in the underexpanded flow regime is related to the change in the jet mode structure from axisymmetric to helical to another at which the normal shock waves are more dominant.[6] This indicates that the pressure ratio/Mach number has a considerable effect on the jet structure, especially for underexpanded jets.

Conclusions

The main features of high-speed twin jets are quite similar to those of low-speed incompressible jets. The flowfield contains three distinct regions, namely, converging, merging, and combining regions. The twin jet interacts and merges, with a downstream development like a circular single jet. The position of maximum velocity/total pressure of the twin jet shifts from the nozzle axis to the plane of symmetry between the jets. The jet flow structure is strongly influenced by the pressure ratio as well as nozzle spacing. Because of the interaction between the jets, the jet axes bend toward each other, and the extent of bending increases with nozzle spacing. In the region close to the nozzle, the width of the twin jet is larger than that of a single jet. Far downstream, the spread rate of the combined jet is slightly lower than that of a single jet for most of nozzle spacing values. In the underexpanded flow region, the jet width shows irregular variation with varying the pressure ratio, and it is not characterized by a fixed behavior as that of a low-speed jet.

References

[1]Elbanna, H., Gahin, S., and Rashed, M. I., "Investigation of Two Plane Parallel Jets," *AIAA Journal*, Vol. 21, No. 7, 1983, pp. 986–991.

[2]Okamoto, T., Yagito, H., Watanobe, A., and Kawamura, K., "Interaction of Twin Turbulent Circular Jet," *Bulletin of the JSME*, Vol. 28, No. 238, 1985, pp. 617–622.

[3]Miller, D. R., and Comings, E. W., "Force Momentum Fields in a Dual Jet Flow," *Journal of Fluid Mechanics*, Vol. 18, No. 7, 1959, pp. 237–256.

[4]Seiner, J. M., Mauning, J. C., and Ponton, M. K., "Dynamic Pressure Leads Associated with Twin Supersonic Plume Resonance," *AIAA Journal*, Vol. 26, No. 8, 1989, pp. 954–960.

[5]Wlezien, R. W., "Nozzle Geometry Effect on Supersonic Jet Interaction," *AIAA Journal*, Vol. 27, No. 10, 1989, pp. 1361–1367.

[6]Gutmark, E., Schadow, K. C., and Bicker, C. J., "Mode Switching in Supersonic Circular Jets," *Physics of Fluids*, Vol. A1, No. 5, 1989, pp. 868–873.