A STUDY OF INTERACTION OF FIVE SUPERSONIC JETS

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Abstract

The spreading features of five supersonic jets, in the configuration of one central bigger jet surrounded by four smaller equi-distant peripheral jets have been studied numerically and experimentally for different Mach numbers and spacing ratios. The computed values are in good agreement with the experimental results. The jets maintain their individual behavior up to twelve diameters and thereafter they merge to form a single jet. For smaller spacing ratio and lower Mach number, the merger occurs earlier compared to higher spacing ratio and larger Mach number. The mass flux rate increases with the spacing ratio. The Reynolds shear stress and turbulent kinetic energy are higher for under expanded jets than for correctly expanded jets and over expanded jets.

Introduction

Supersonic jets are encountered in a variety of engineering applications such as high speed civil transport aircrafts, rockets, V/STOL aircrafts, strap-on boosters etc. Raghunathan and Reid [1] studied the problem of multiple supersonic jets for five and nine nozzles with one central jet. The main objective was to achieve noise reduction. Vijayakumar et al. [2] studied numerically the spreading features of five supersonic jets at M = 1.0 to 1.5 and spacing ratios of 1.25, 1.67 and 2.08. The five jets coalesce to form a single jet at about ten diameters. Manohar [3] had studied numerically five supersonic jets with and without canting (cant angle = 4°) in external flow at M = 1.5, 2.0 and 2.5 and spacing ratios of 1.5, 2.0, 2.5, where the spacing is the distance between the centers of the central bigger jet and that of any smaller peripheral jets.

Zaman [4] experimentally obtained the mass flux data for a supersonic jet at M=1.63 from six different nozzles of same exit area. The biggest increase in jet spreading is obtained when the tabs are used at the exit of a rectangular jet. The tabs produce a pair of vortices, which enhance jet spreading. The screech tones are not eliminated but their amplitudes are reduced. Gutmark and Grinstein [5] have shown that the non-circular geometries have higher entrainment than circular jets.

Strykowski et al. [6] experimentally studied the enhanced mixing in supersonic jet (M=2) using annular counter flow. In this paper, the experimental studies are done on five jets of unequal diameters. The five supersonic jets corresponding to exit Mach number of M = 1.25, 1.5 and 1.75 and various nozzle spacings of S/D = 2.1, 2.5 and 3.0 have been studied. Here, S is the spacing between the centers of the central jet and the peripheral jets and D is the throat diameter of the bigger jet. Numerical studies are also done using the FLUENT code. A numerical study of five equal jets is done for comparison. A shorter version of the paper by Ramjee, et. al [7] is presented in the Tenth Asian congress of FLUID Mechanics at Sri Lanka.

Experimental Details

A reciprocating compressor, with a discharge of 14.6m³/min, driven by a 3-phase 150 hp electric motor is used to charge two storage tanks of 10m³ capacity each (Fig.1). The compressed air from the storage tank flows into the settling chamber through a pressure-regulating valve. A three-dimensional traverse, with 6 degrees of freedom and motorised in axial and radial directions is used to locate the pitot tube (OD = 2.5mm and ID = 1.5mm) to measure the stagnation pressure in the jet. A pressure transducer connected with the data acquisition system is used to record the pressure values in the computer. The static pressure is measured using a cone type probe with two holes in the periphery at a distance of 15 mm from the tip. Axisymmetric convergent-divergent nozzles were fabricated for M = 1.25, 1.5, 1.75 and 2.0. The throat diameter of the bigger jet (D) is 12mm and that of the smaller jet (d) is 6 mm. Depending on the area ratio, the exit diameter of the nozzles has been varied for the par-

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Fig. 1 Schematic of the experimental set up

Fig. 2b Quarter geometry

Fig. 2a Total geometry

Mach number. Different spacer plates are used for the three spacing ratios namely S/D = 2.1, 2.5 and 3.0. The measurements are made at X/D = 2, 4, 6, 8, 10, 15, 20, 25, 30 and 35. Precautions were taken during the experimental runs to achieve proper results. The experiments were conducted twice to ensure repeatability and average was taken in each case. The error involved in maintaining pressure is around ±1.7%. The machining accuracy of the nozzle is ±1%. The five jets at M= 2.0 are studied numerically only because of experimental limitations.

Numerical Procedure

In Cartesian tensor notation, the equations of continuity, momentum, energy and equation of state for a compressible viscous flow are given by:

\[ \frac{\partial}{\partial x_i} (\rho U_i) = 0 \] (1)

\[ \frac{\partial}{\partial x_i} (\rho U_i U_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} \] (2)

where

\[ \tau_{ij} = \left[ \mu \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) - \frac{2}{3} \mu \frac{\partial U_i}{\partial x_l} \delta_{ij} \right] \] (3)

\[ \frac{\partial}{\partial x_i} (\rho U_i h) = \frac{\partial}{\partial x_i} \left( k \frac{\partial T}{\partial x_i} + U_i \frac{\partial p}{\partial x_i} + \frac{\partial U_i}{\partial x_j} \frac{\partial U_i}{\partial x_j} \right) \] (4)

\[ p = \rho R T \] (5)

The local viscosity \( \mu \) is taken as a sum of the laminar and turbulent viscosities. The turbulent viscosity, in turn, is calculated from the k-\( \varepsilon \) model. The above set of equations has been solved using FLUENT code.

A five-jet flow configuration consisting of a central larger jet surrounded by four smaller jets arranged on the periphery of a circle at equal interval is shown in Fig.2a. In this problem, there is four-fold symmetry and hence only one-quarter geometry is chosen for simulation as shown in Fig.2b. In order to test the grid independence of the predicted solutions, grids with 62x31x31, 72x41x41, 92x31x31 nodes have been employed. The prediction of Mach number along the axis of the central jet is shown in Fig.3. The centerline predictions do not show marked variations for the range of grids employed, even though the total number of nodes employed in each grid is significantly different. Hence, a grid of 72x41x41 has been used for all further computations. Grid points are clustered in such a way that the steep gradients existing near the nozzle exit and jet boundaries are captured accurately.
Results and Discussions

a) Total Pressure Profiles

The total pressure profiles at various axial locations are shown for nozzle exit Mach number equal to 1.25 and S/D = 2.1 in Fig. 4. Here both the experimental and numerical results are shown and they are in good agreement except in the near field (i.e. up to X/D = 4) where complex shock structures are encountered. The deviations can be due to the interference of the probe with the shock cells in the near field and the almost laminar behaviour of the supersonic jets in the initial zone is not captured well by the turbulence model used in the numerical simulations. However, in the far-field region the comparison between experimental data and theoretical predictions is reasonably good.

It is seen from the profiles that the smaller jets in the periphery decay at faster rate compared to that of the central jet. This is due to the fact that the decay distance scales approximately linearly with the jet diameter. Also, the smaller jets bend more towards the larger jet due to entrainment and merge to form a single jet, which adds to their rates of decay. The merger distance for the present five-jet configurations is of the order of X/D = 12. In all the cases studied, it was observed that a low sub-atmos-
pheric pressure value occurs in the region between jets due to the combined entrainment of the entrapped fluid by all the five jets. However, since the entrainment associated with this configuration is symmetric, the axis of the final combined jet is not altered and is the same as the axis of the central jet. The total pressure profiles for M=1.5 and M=2.0 are not shown due to limitation of the size of the paper.

b) Mass Flow Rate Profiles

The variation of dimensionless mass flow rate with axial distance is shown in Fig.5 for various nozzle spacings. The mass flow rate at the inlet plane is used as the scale for normalization. It is evident from the figure that the mass flow rate increases with increase in inter-nozzle spacing. In the near field, there is no marked variation in the mass entrained for the different spacings considered. However, a significant increase occurs in the entrainment for larger spacings and intermediate axial locations. The above trend is in conformity with the argument that bending of the jets towards each other induces greater lateral velocities and hence larger level of entrainment. Fig.6 shows the effect of Mach number on the mass flow rate for S/D = 2.1. The mass flow rate decreases with the increase in exit Mach number.

c) Effect of Exit Pressure Ratio

When the nozzle exit pressure ratio is varied, from 0.8,1.0,1.3 in supersonic jets, one can get over-expanded, correctly-expanded and under-expanded jets depending on the stagnation pressure. In the single jet experiments, it was found that over-expanded jet decays faster than the two cases because of strong shocks. In the under-expanded jet, expansion outside the nozzle occurs and hence lower rate of jet decay and entrainment. The Reynolds shear stress and turbulent kinetic energy are higher for the under-expanded jet than the other two cases. Some of the results are published in 30th Conference of FMFP (pp. 487-494), 2003. In the five jets configuration, similar trends are observed. Fig.7 shows the mass flow rates \( \dot{m}/\dot{m}_e \) at various axial locations for M=1.25 and spacing ratio S/D=2.1 and \( p_o/p_a =2.07,2.59 \) and 3.37. The mass flux increases with axial distance and the middle line is for the correctly-expanded jet. Higher mass flux is observed in the over-expanded jet than the under-expanded jet. The variation of Reynolds shear stress \( \overline{u'v'}/u'_e^2 \) with Y/D is shown in Fig.8 for various axial locations X/D =4,6,8,10,15,20,25 and 35 for M=1.25, S/D=2.1. The val-

![Fig. 5 Comparison of mass flow rate for various nozzle spacings (at M=1.25 and p_o/p_a=2.591)](image)

![Fig. 6 Comparison of mass flow rate for various Mach numbers (at S/D=2.1)](image)

![Fig. 7 Comparison of the local mass flow rates for various pressure ratios at M=1.25 and S/D=2.1)](image)
values of the shear stress are higher for the under-expanded jets than the other two cases. At $X/D=4$, three distant peaks are seen. The first peak value is for the central jet shear layer and the other two peaks are for the peripheral jet shear layer. The shear stress value of the peripheral jet decreases faster and at $X/D=15$, there is only one peak value similar to a single jet. Similar results are got for $M=1.5$ and $M=1.75$ and they are not shown here. The turbulent kinetic energy $k/u_0^2$ is plotted against $Y/D$ for $M=1.25$, $S/D=2.1$ in Fig. 9 for different axial locations. These are numerical predictions. The turbulent kinetic energy is higher for the under-expanded jets because of flow acceleration. At $X/D=4$, three peak values are seen and at $X/D=10$, two peak values are seen at $X/D=20$, only one peak value is seen. The turbulent values decay faster in the smaller peripheral jets and then all the jets merge into a single jet. Some slight differences can be seen in the turbulent kinetic energy in the inner and outer shear layer of the peripheral jets up to $X/D=8$.

d) Comparison of Equal Jets and Unequal Jets

Figure 10 shows the Mach number profiles for $X/D=2$ to 35 at $M=1.5$, $S/D=2.1$, $p_o/p_a=3.67$ for the unequal jets and the equal jets. When all the five jets are equal, the momentum is higher and hence decay is slower. The merger distance is longer for the equal jets than the unequal jets. The unequal jets merge at $X/D=20$, while the equal jets merge at $X/D=25$. The center-line variation of Mach number, total pressure, static pressure and static temperature is shown in Fig. 11 for $M=1.5$, $S/D=2.1$ and $p_o/p_a=3.67$. The equal jets decay more slowly than the central jets, because of larger momentum. The bending of peripheral jets will be lower for the equal jets and hence the mass flux $m/m_a$. In Fig. 12, the mass flux ratio is plotted against $X/D$ for $M=1.5$ and $S/D=2.1$. The mass flux ratio is more for the unequal jets than the equal jets. The unequal jets entrain more mass by mixing faster with the ambient fluid. The Reynolds shear stress $u'v'/u_0^2$ is plotted against $Y/D$ for $M=1.5$, $S/D=2.5$ for the equal jets and unequal jets in Fig. 13 for various axial locations from $X/D=4$ to 35. The shear stress values decay slowly for the equal jets case compared to the unequal jets configuration. At $X/D=10$ and 15, the differences, between equal jets and unequal jets, are spectacular. When the peripheral jets are of smaller diameter, the momentum is less and the mixing is faster. The merger of all jets occurs earlier for the

Fig. 8 Variation of Reynolds shear stress for five jets at $M=1.25$ and $S/D=2.1$ [0-0-0-0- over-expanded ($p_o/p_a=2.07$); correct-expended ($p_o/p_a=2.59$); under-expanded ($p_o/p_a=3.37$)]
Fig. 9 Variation of Turbulent kinetic energy for five jets at $M=1.25$ and $S/D=2.1$ ([0-0-0-0-0 over-expended ($p_d/p_a=2.07$); correctly-expended ($p_d/p_a=2.59$); under-expended ($p_d/p_a=3.37$)])

Fig. 10 Comparison of Mach number profiles for five equal and five unequal jets at $M=1.5$ and $S/D=2.1$ and $p_d/p_a=3.67$ (unequal jet; equal jet)
unequal jets. At X/D=20 the shear stress values of smaller peripheral jets decayed while even at X/D=25, the values of shear stress of equal jets did not decay sufficiently. The turbulent kinetic $k/\nu^2$ shown in Fig.14 also displays similar trends. The three distant peaks seen at X/D=4 decay, and at X/D=15, the values of unequal jets is lower than that of equal jets. Because of lower momentum of smaller jets, the decay is faster for mean velocity, shear stress and turbulent kinetic energy. In Fig.15, the effect of varying stagnation temperature from 300K to 3000K is shown for M=1.5, S/D=2.1 and $p_o/p_u=3.67$. The Mach number variation along the axis is shown in Fig.15d. At lower stagnation temperature, the Mach number decays faster than at higher stagnation temperature. The effect is relatively small and it is seen beyond X/D=20 when the stagnation temperature is altered by a factor of ten.
Fig. 13 Comparison of Reynolds shear stress for five unequal and equal jets at $M=1.5$ and $S/D=2.5$ and $P/P_n=3.67$ (unequal jet; equal jet)

Fig. 14 Comparison of turbulent kinetic energy for five unequal and equal jets at $M=1.5$ and $S/D=2.5$ and $P/P_n=3.67$ (unequal jet; equal jet)
The five jets maintain their individual characteristics up to a distance of X/D = 12. Thereafter, they coalesce to form a single jet. The merger distance increases for larger spacing ratio and higher Mach Number.

All the jets entrain ambient air from the inter-jet region and hence a sub-atmospheric region is formed which causes the jet bending. The jets spread with distance due to entrainment of fluid from the ambient atmosphere, resulting in a net increase in mass flow rate.

The peripheral jets bend towards the central jet and mix to form a single jet at around X/D = 12. The five equal jets merge at a larger distance because of larger momentum.

The mass flow rate ratio is lower for the five equal jets compared to the unequal jets.

Fig. 15 Effect of temperature on five jet interaction at M=1.5, S/D = 2.1 and p₀/p₀ₙ = 3.67
• The axis of the central larger jet is not affected by the presence of surrounding smaller jets because of symmetric entrainment of ambient fluid.

• Over-expanded jets have higher mass flux ratio compared to correctly-expanded jets and under-expanded jets.

• The Reynolds shear stress and turbulent kinetic energy are higher for the under-expanded jets because of flow acceleration.

• The spacing between the jets is seen to affect the mixing of five-jets significantly. With increase in spacing, the jet bending increases. The merger distance also increases, which can be attributed to the jets retaining their individual characteristics for a larger axial distance due to the wider separation between the jets.

• As the spacing increases for a given Mach number, the mass flow rate increases. For a given spacing, the mass flow rate decreases with the increase in exit Mach number.

References


