Turbulent Mixing of Multiple Co-Axial Gaseous Fuel Jets in a Supersonic Airstream

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Theme

WHILE much information on fuel injection and mixing in supersonic flows has accumulated, the design of a Scramjet engine is still limited by inadequate fuel diffusion from isolated injectors. A solution which appears attractive is downstream facing jets in clusters. The phenomena to be investigated will be the effect on mixing of the spacing between the individual nozzles and the interaction between the different jets after they start merging. The only relevant previous work is the preliminary study by the authors[1] where tests with a five-port injector on a cruciform strut showed no appreciable effect of the nondimensional spacing, S/D, down to a value of 2.8. The present report describes the results of an experimental and analytical study of a variable spacing, four-jet injection system in a Mach 4 airstream utilizing helium as the injectant. The major parameter varied was the jet spacing, (S/D of 1.5—3.0), and the principal data consist of helium concentration distributions. Mach number surveys downstream of the injectors and schlieren pictures were also made. An approximate analysis for such problems is presented and compared to the experimental results.

Contents

Experiments: Tests were conducted in a 9 in. × 9 in. supersonic wind tunnel at Mach 4.0. The nominal tunnel total pressure and temperature were 154 psia and 530°R. The injector model shown in Figs. 1a and b consisted of four separate injectors arranged in pairs. Each injector had a stainless steel support strut, which also served as the injectant feed line, and an injection nozzle. The nozzles were made of 0.25 in. o.d. tubes brazed to the struts. The upstream tips of the nozzles are 7° half angle cones brazed to the nozzles in such a way that the side of the cone towards the center of the model was parallel to the flow in order to achieve as undisturbed a flow as possible in the region between the nozzles. The total injectant flow rate was 1.83 lb/min. To achieve variable S/D, the bases of the struts were machined in a series of steps parallel to the flow and fitted into a frame into which matching steps were machined.

Pitot pressure and helium concentration distributions were obtained to define the flowfield. A special nineteen-port rake was fabricated that had ports arranged along the vertical, horizontal and 45° diagonal directions.

In all gas sampling runs, the rake was positioned so that the middle probe was centered in line with the geometric center of one injection nozzle. Pitot pressure runs were made with the rake in various transverse locations at a given axial station to map out the disturbance field.

For the pressure runs, the leads from the rake were connected to a Scani-valve. When gas sampling tests were being run, the leads from the rake were run to a 14 bottle collection cart, and analysis of the gas samples was subsequently done with a gas chromatograph.

Figure 2 gives representative helium concentration profiles across the nozzle in the vertical plane. The data behave in the expected manner, that is, the concentration is highest at the center of the nozzle and falls off towards the edges; the maximum concentration falls off with axial distance and the concentration is lower for larger S/D.

Figure 3 is a plot of the maximum concentrations (disregarding their actual radial locations although generally this was along the original axis of the jet) as a function of axial distance for different S/D's. As seen in this graph, S/D has a

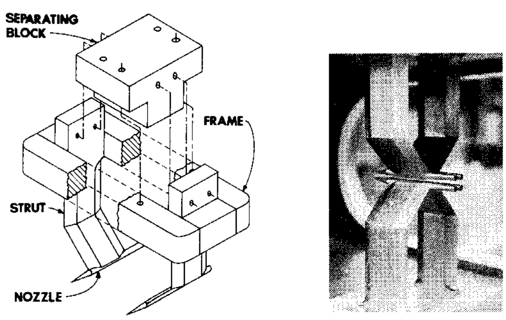

Fig. 1 Exploded view of the injector model.

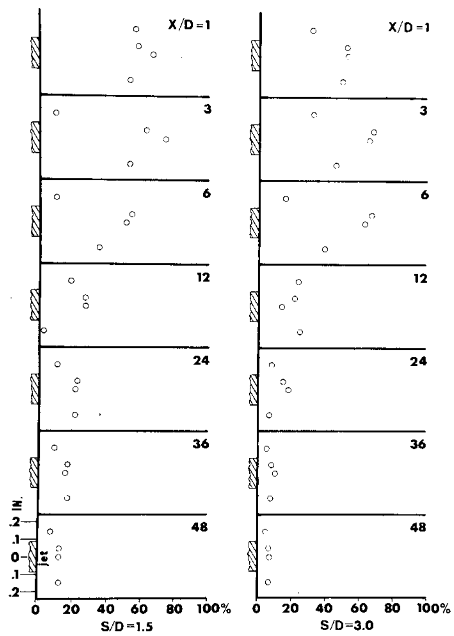

Fig. 2 He concentration (mass fraction, %, He) vertical profiles.

Presented as Paper 74-1157 at the AIAA/SAE 10th Propulsion Conference, San Diego, California, October 21-23, 1974; submitted December 2, 1974; revision received March 5, 1975. Full paper available from the National Technical Information Service, Springfield, Va., 22151, as NASA CR-2469 at the standard price (available upon request). This work was performed under Contract NAS1-10233 with the Langley Research Center.

Index categories: Airbreathing Propulsion, Hypersonic; Jets, Wakes, and Viscid-Inviscid Flow Interactions.

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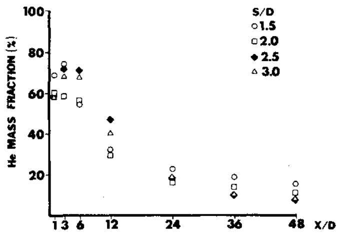

Fig. 3 Maximum He concentration as a function of distance from injector for various S/D's.

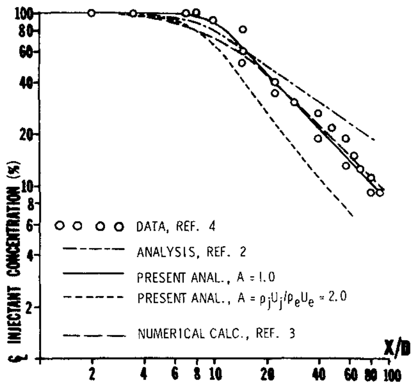

Fig. 4 Comparison of present theoretical calculation with experimental data from Ref. 4.

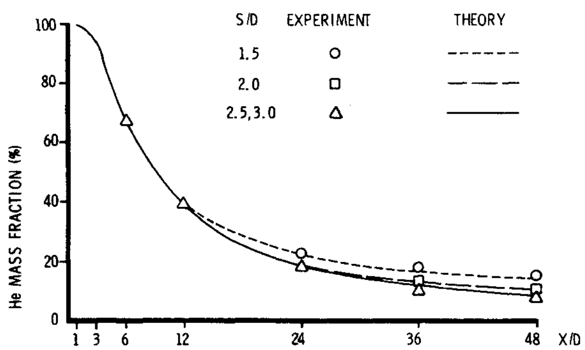

Fig. 5 Centerline He concentration vs X/D at jet centerline; comparison between theory and experiment.

somewhat inconsistent effect on the concentration at lower X/D's, but starting at $X/D=36$ the influence of S/D is clear and as expected—lower concentration at higher S/D.

Analysis: The work follows that of Libby,[2] but several changes are made that produce a significant improvement in the predictions. We begin with the boundary-layer equations for axisymmetric flow written in Von Mises coordinates

$$u_x = (1/u_e\psi)\left([\epsilon\rho^2 r^2 u/\rho_e^2 u_e \psi^2]\psi u_\psi\right)_\psi \tag{1}$$

and choose to affect a linearization directly.

$$[(\rho^2\epsilon)r^2 u/\rho_e^2 u_e \psi^2] \approx (\rho\epsilon/\rho_e)A(x) \tag{2}$$

where $A(x)$, is an, as yet unspecified, stretching factor to make the approximation as reasonable as possible.

Introducing a new streamwise variable $\xi(x)$.

$$\xi \equiv \int_0^x \frac{(\rho\epsilon)A(x)}{\psi_j \rho_e u_e}\, dx \tag{3}$$

we get

$$u_\xi = \psi_j/\psi(\psi u_\psi)_\psi \tag{4}$$

It is important to note that since this equation is linear, the solution for the three-dimensional flow produced by multiple jets can be found from the axisymmetric solution for a single jet by simple algebraic superposition.

It remains now to specify a form for the eddy viscosity, select $A(x)$ and write boundary conditions. Solving this system will produce a solution for $u(\xi,\psi)$ which can be converted to $u(x,r)$. This leaves the temperature and concentration fields unknown, however, generalized Crocco integrals can be used to relate these to the velocity field.

The eddy viscosity is taken as suggested in Ref. 3. Turning back to the "stretching factor," $A(x)$, it can be shown that at $x=0$, when going from the center of the nozzle outward, the value of $A(0)$ will tend to $\rho_j u_j/\rho_e u_e$ after starting with a value of 1.0 near the axis. We found a suitable form where "A" could be taken as a simple constant for any particular problem. Consider the air (with tracer) into air experiments of Ref. 4. Various results are shown in Fig. 4 which includes the experimental data, Libby's prediction, a prediction obtained from a numerical solution using the eddy viscosity model of Ref. 3 and two predictions from the present analysis depending on whether A is taken as simply unity or $A=\rho_j u_j/\rho_e u_e=2.0$. With $A=1.0$, excellent agreement with the data and the exact numerical solution is obtained. Next, calculations were made for the present experimental cases using $A=1.0$ and $A=\rho_j u_j/\rho_e u_e=0.3901$. As before, the smaller value of "A" provided the most accurate prediction. This comparison was made for the $S/D=3.0$ case, since it behaved essentially as an isolated jet. On this basis, we propose the following simple rule for selection of A: "The value of A should be chosen as unity or $\rho_j u_j/\rho_e u_e$, whichever is smaller."

The prediction for the centerline concentration for all experimental cases are shown in Fig. 5 in which the following points should be noted: injectant concentration depends on S/D up to S/D of 2.5 both for theory and experiment; the rate of change of the concentration as a function of S/D is similar for experimental results and theoretical calculation; the agreement between theory and experiment is also good for the absolute values of the concentration.

References

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