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Numerical Modelling of Liquid Ramjet Combustors

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ABSTRACT

The liquid fuel ramjet system employing a subsonic side-dump combustor is simulated in the present study, and the predictions are compared with the available experimental data. The complex combustion phenomenon in a ramjet combustor has been carried out using probability density function (PDF) approach. The complexity arises because of the mixing of fuel and air streams, and the burning of the resultant mixture, within the confined space of the combustion chamber. The predicted numerical results have been validated with the results available in open literature for a two-dimensional case and with in-house experimental data for a three-dimensional case. The methodology allows different designs to be evaluated quantitatively based on the performance metrics such as combustion efficiency, flame stability, etc.

Keywords: Ramjet, dump combustor, numerical simulation, aerodynamic flame stabilisation

1. INTRODUCTION

Combustion phenomena in a ramjet combustor are complex and involve a very high degree of nonlinearity, which are related to the mixing of the fuel and air streams, and the burning of the resultant mixture, within the confined space of the combustion chamber. The flow field within the chamber consists of regions of flow recirculation, separation and reattachment. The presence of multiple jets adds to the complexities of the flow field, in the form of recirculation zones surrounding the side-air jets near the wall. Since such compact combustors do not normally have any structural flame-holding mechanisms, these have to depend on aerodynamic stabilisation of the flame, provided by the recirculatory flow regions. Proper mixing between fuel and air becomes a crucial factor, which determines the optimal design of these combustion systems.

Crowe[1], *et al.* developed a special model for the analysis of gas-droplet flows which is also known as the particle-source-in-cell (PSI-CELL) model. Shahaf [2], *et al.* investigated two-dimensional liquid fuel combustion phenomena both experimentally and analytically on different dump combustor geometries without central jet. Jones and Whitelaw[3] discussed the calculation methods for reacting turbulent flows in detail. Roy [4], *et al.* experimentally tested the combustor performance of a gas generator ramjet with four-side-air-inlets without any central injection and concluded that the system of vortices in the head region is crucial for the stable operation of the combustor. Stull[5], *et al.* investigated the dual-side-air-inlet dump ramjet combustor using a liquid fuel injection. The flow-field characteristics of a three-dimensional side-air-inlet dump combustor were numerically investigated by Stull[6], *et al.* by varying the position of the dome plate. In a two-

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dimensional dump-type model of combustions chamber commonly employed in ramjets, the effect of variations in dump angle on the turbulence characteristics was investigated by Manjunath[7], *et al*. The effect of side-inlet angle on the flow field of a three-dimensional dump combustor in which the side jets are exactly opposite to each other was considered by Yen and Ko[8]. The combustion characteristics of a ramjet combustor were experimentally studied by Inamura[9], *et al*. Jiang and Shen[10], numerically analysed the spray-combustion flow in a side-dump ramjet combustor attached with four symmetric inlets. Grohens[11], *et al*. employed an innovative numerical method for global performance prediction of ramjet combustion chambers which consisted of four stages. Initially, a non-reactive Reynolds-averaged Navier-Stokes (RANS) computation was carried out followed by a Lagrangian calculation of the liquid phase (fuel). Subsequently, the transport equation was solved and the combustion efficiency was obtained with a chemical kinetic model for any equivalence ratio.

In the present study, a flow model has been developed that could predict the effects of air-inlet dump angle, air/fuel ratio, and size of the fuel droplets on combustion in the case of a two-side-inlet (90^{o} apart) dump ramjet combustor.

2. SOLUTION METHODOLOGY

The liquid fuel ramjet system employing a subsonic side-dump combustor is simulated in the present study and compared with the available experimental data.

The following assumptions have been invoked while formulating the governing equations, to simplify the analysis:

Flow is incompressible; buoyancy and radiation effects are negligible; chemical kinetic steps are much faster than the convective diffusion processes; property variations with temperature are considered mainly for the specific heat, thermal conductivity, and viscosity of the gas phase. In cases, where the variations are difficult to incorporate either because of computational difficulties or lack of empirical data, constant (average) values have been assumed. The fuel is taken to be kerosene, introduced in the form of a spray normal to the incoming airflow in the rectangular-inlet arms. Spray droplets are assumed to be spherical, droplets striking the walls are assumed to evaporate instantaneously while those crossing the line of symmetry are assumed to be reflected back.

Based on the above assumptions, the governing equations for the gas-phase mixture, fuel, and oxidiser species, and the dispersed phase of burning spray droplets are solved to obtain solutions for the steady-state operation of the combustor.

The mixture fraction/probability density function (PDF) modelling approach involves the solution of transport equations for one or two-conserved scalars (the mixture fractions). In this approach, transport equations for individual species are not solved. Instead, individual component concentrations for the species of interest are derived from the predicted mixture fraction distribution. Physical properties of chemical species and equilibrium data are obtained from the chemical database. The chemical database is accessed to obtain the thermodynamic and physical data for reacting the mixture components at the specified system pressure and over the temperature range of interest in the model developed. A look-up table which contains mean (time averaged) values of specified mole fractions, density and temperature as a function of mean mixture fraction, mixture fraction variance, and enthalpy is prepared. The look-up table is the stored result of the integration of equations in the PDF modelling of turbulence-chemistry interaction. The look-up table will be used by the solver to determine the mean species mole fractions, density, and temperature from the values of mixture fraction, mixture fraction variance and enthalpy as these are computed during the calculation of the reaction.

3. COMBUSTION MODEL FOR RAMJET APPLICATIONS

The liquid fuel ramjet system employing a subsonic side-dump combustor is simulated in the present study and compared with the available experimental data. In side-dump combustion chambers, the impingement of two or more jets is an important feature of the combustor flow field. Also, in these combustors, the recirculatory zones formed due to the sudden area enlargement between the air-intake ducts and the combustion chamber act as flame holders, hence their dimensions affect the combustion intensity and efficiency. The present configuration uses two rectangular side-mounted air intakes, which are separated radially by 90° (Fig. 1). The rectangular air intakes in this configuration give angle of attack capability, which is desirable in certain applications.

The boundary conditions for the jet flows inside the dump combustor considered in the present study (Fig.1) are:

- At the side-air-inlet, mass flow rate, total temperature and total pressure are specified.
- At exit boundary, $p = p_{atm}$ and the second derivative in the axial direction has been set to zero for other variables.
- The walls have been taken to be adiabatic and no-slip boundaries with the species mass flux equal to zero.

The common data used in the simulation (unless specified otherwise) are:

Fuel particles mean diameter	: 20 µm
Fuel temperature at inlet	: 300K
Combustor pressure	: 4 bar
Air-inlet temperature	: 400K and
Air mass flow rate	: 7 kg/s

4. RESULTS AND DISCUSSION

4.1 Grid-independent Study

Simulations of the three-dimensional, two-side-inlet ramjet dump combustor were carried out with three different grids having 74970 cells, 91182 cells, and 134953 cells. Starting with baseline coarse grid, refinement of the grid based on gradients of temperature and pressure has been carried out to arrive at the final grid.

The centreline temperature along the combustor axis for these three grids is shown in Fig. 2. Temperature values are grid independent in the dome-end of the combustor as well as the region towards the exit plane. However, in the vicinity of the side-air jet-mixing location, the coarse grid over-predicts the temperature by 6 per cent to 10 per cent when compared with the intermediate or fine grids. As a compromise between reasonable accuracy and computational time, all the simulations have been carried out on the intermediate grid with 91182 cells.

4.2 Convergence Criterion

The convergence criterion for the iterative solution procedure of the present study is that the normalised overall residue value be less than or equal to 10^{-3} for continuity, velocity, turbulent kinetic energy and dissipation rate, whereas it is 10^{-6} for both enthalpy and species concentration. Under-relaxation was also employed for all the solution variables, in view of the highly nonlinear nature of the governing equations.

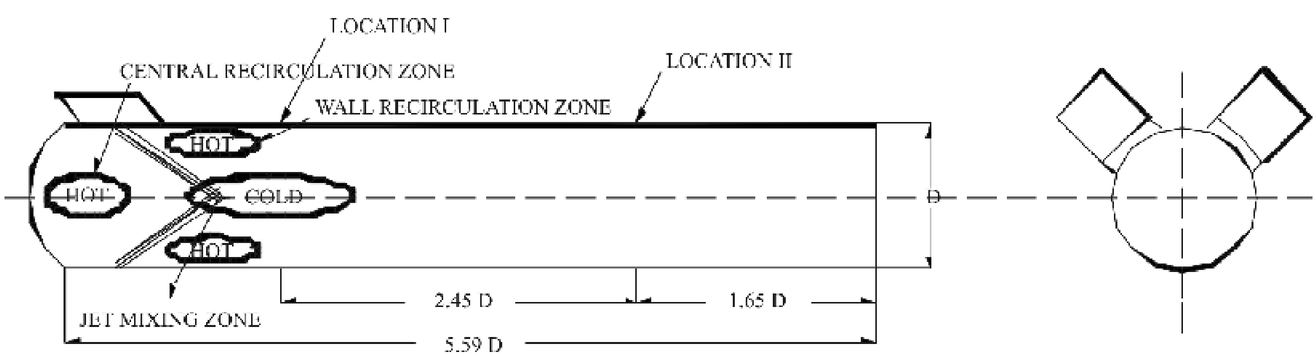

Figure 1. Ramjet dump combustor configuration used for simulation.

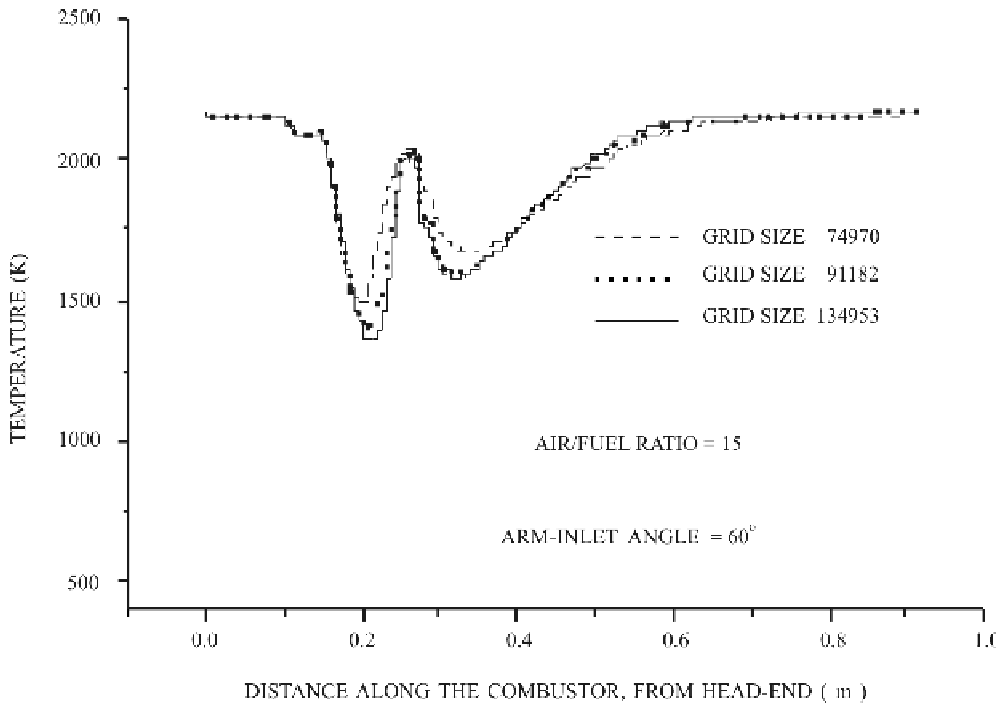

Figure 2. Static temperature variations along the combustor axis.

4.3 Validation Study

Before proceeding with the detailed parametric study of combustor performance, a validation study has been carried out. Here, two-dimensional simulations have been carried out for the problem studied by Cherng[12], *et al.*, and the results compared with those reported in their work.

It can be seen from Figs 3 and 4 that there is reasonably good agreement in the flow pattern as well as the temperature distribution between the present study and those of Cherng[12] *et al*. The location and size of recirculation zones, which facilitate and stabilise combustion, are predicted well by the present calculations.

Validation studies have also been carried out to compare the predicted numerical results with the experimental data obtained from the tests conducted at the Liquid Ramjet Combustor Test Facility of Defence Research & Development Laboratory (DRDL), Hyderabad. Tests were carried out on the baseline combustor configuration for three air-mass flow rates of 7 kg/s, 5 kg/s, and 2.5 kg/s with an air/fuel ratio of 15. A comparison of the numerical and the experimental data obtained at the Ramjet Propulsion Division is given in Table 1.

Table 1. Comparison of numerical predictions with experimental data

Air mass flow rate (kg/s)	Temperature (K) Location I (4.10 D from the nozzle-end) Expt error ± 2%	Location I Present study	Location II (1.65 D from the nozzle-end) Expt error ± 2%	Location II Present study
7.46	2123	2115	1973	2002
5.97	2023	2005	1873	1902
3.20	1973	1988	1823	1850

The data available for comparison is scanty due to the hostile environment prevalent in the actual ramjet combustor. Besides, the static tests conducted at the DRDL had various other objectives also. The predictions showed a fairly good agreement with the limited experimental data available.

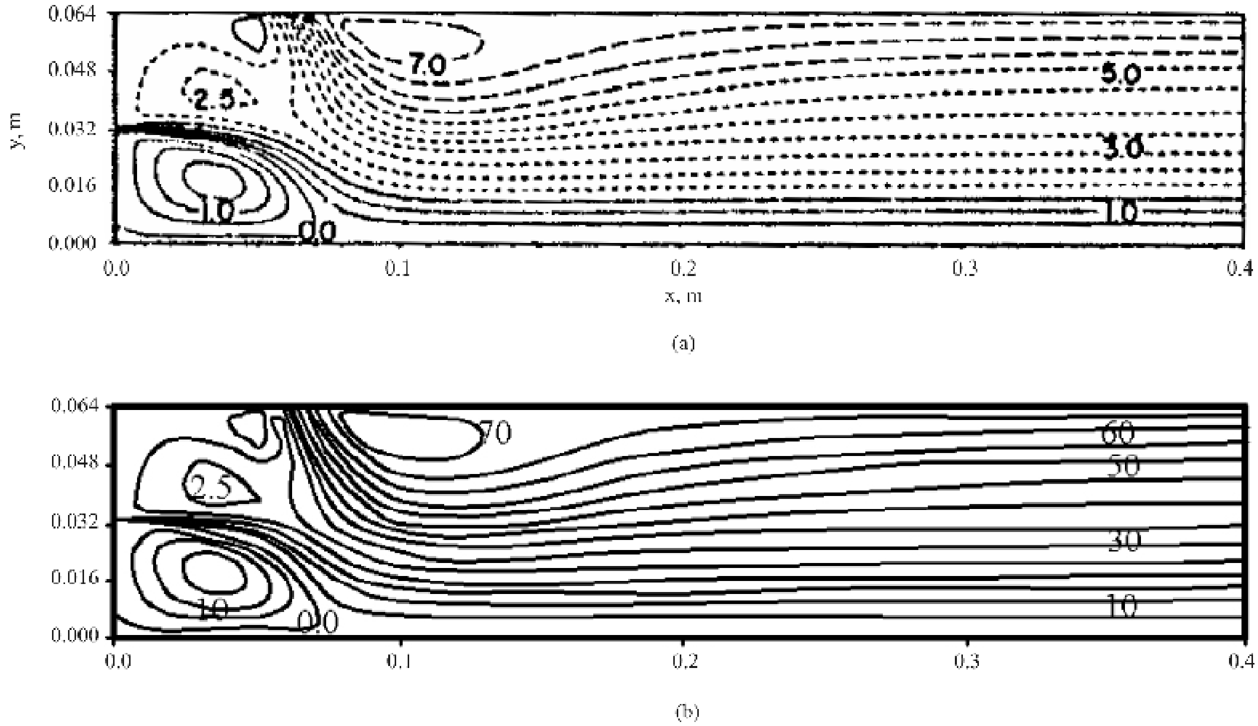

Figure 3. Streamline pattern: (a) Cherng[1], *et al.* and (b) present study (numerical).

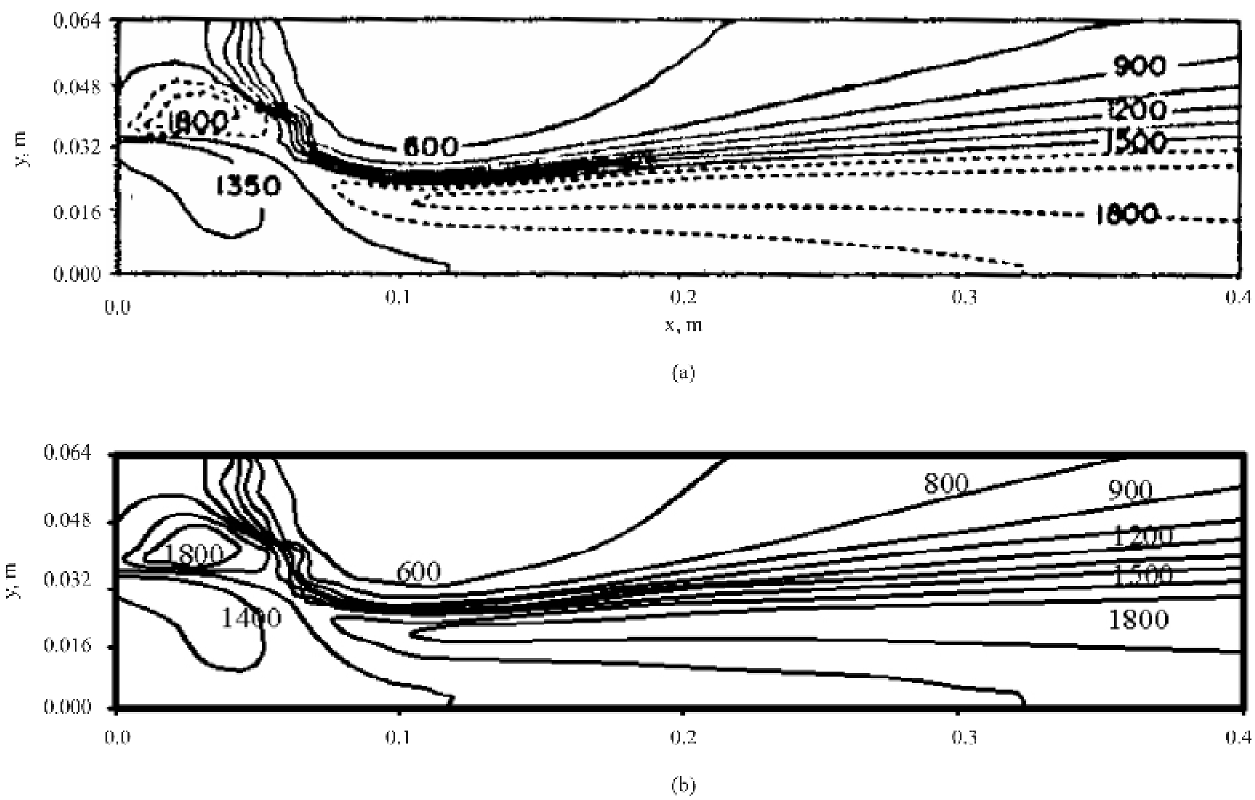

Figure 4. Temperature (K) contours: (a) Cherng[1], *et al.* and (b) present study (numerical).

4.4 Parametric Studies

Extensive parametric studies of a two-side-inlet (90° apart) dump combustor have been carried out. The effects of critical parameters such as air-inlet dump angle, air/fuel ratio, and mean droplet diameter of the fuel spray on the performance of the ramjet combustor have been studied in detail.

4.4.1 Effect of Air-inlet Dump Angle

The flow field in the dome region of the combustor is greatly affected by the air-inlet dump angle. This is due to the fact that dump angle influences the size and strength of the recirculation zones formed. Higher temperatures are observed in the dome region as well in the downstream portion, where recirculatory eddies are established. It is evident that the recirculatory eddies provide aerodynamic stability to the combustion zone. Lower temperatures are observed in the central portion because of the impingement and mixing of the cold-air jets coming from the air intake. In Fig.5, the variation of axial velocity along the centreline is shown. Before the jet impingement point, velocity values are small and negative in magnitude, indicating the presence of a recirculation zone between the two air jets close to the head-end. The size of this recirculation zone decreases with increase in dump angle (since jet merger point moves closer to the head-end), but the strength of recirculation increases. The variations of temperature along the centreline of the combustor for different dump angles is shown in Fig. 6. Due to the presence of stronger recirculation at a high dump angle, it is seen that the temperature in the head-end region increases. However, there is a dip in temperature near the point of impingement of the jets due to the mixing of high-speed cold air in this region. At larger axial distances, due to better mixing between the hot and the cold gases, combustion attains completion and the local temperature value is close to the adiabatic flame temperature. For a dump angle 30°, it is seen that the recirculation zone in the head-end region is not very effective and hence temperature values are relatively lower as compared to the cases with dump angle of 45° and 60°.

Velocity vectors shown in Fig.7 corroborate the abovementioned trends. Contours of temperature for 30°, 45° and 60° dump angles are given in Fig. 8. Contours of temperature and the contours

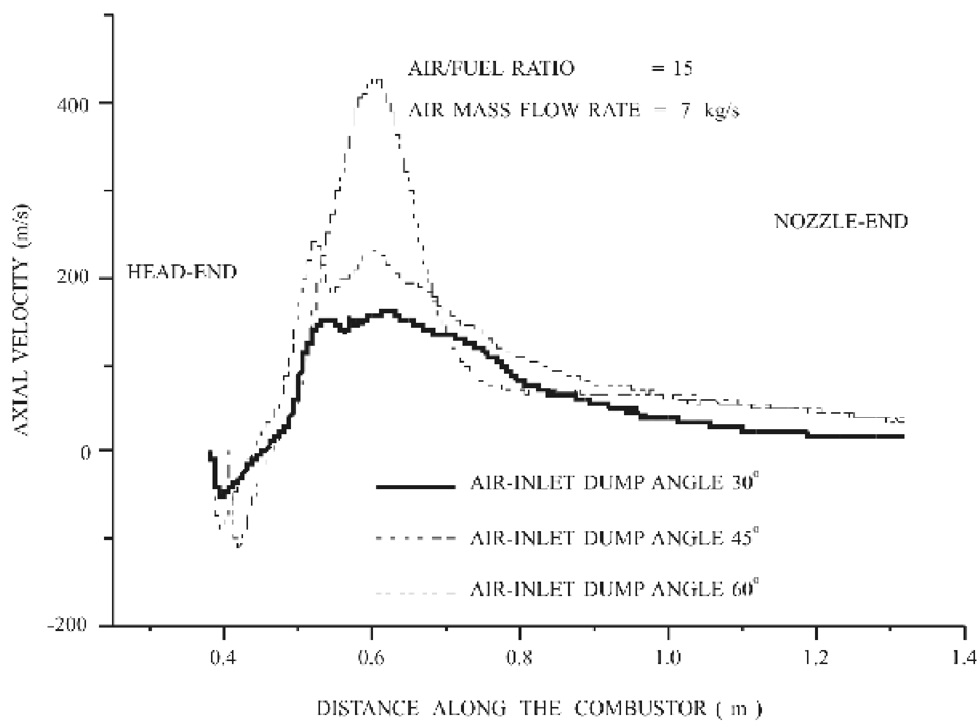

Figure 5. Effect of air-inlet dump angle on centreline value of *u* - velocity.

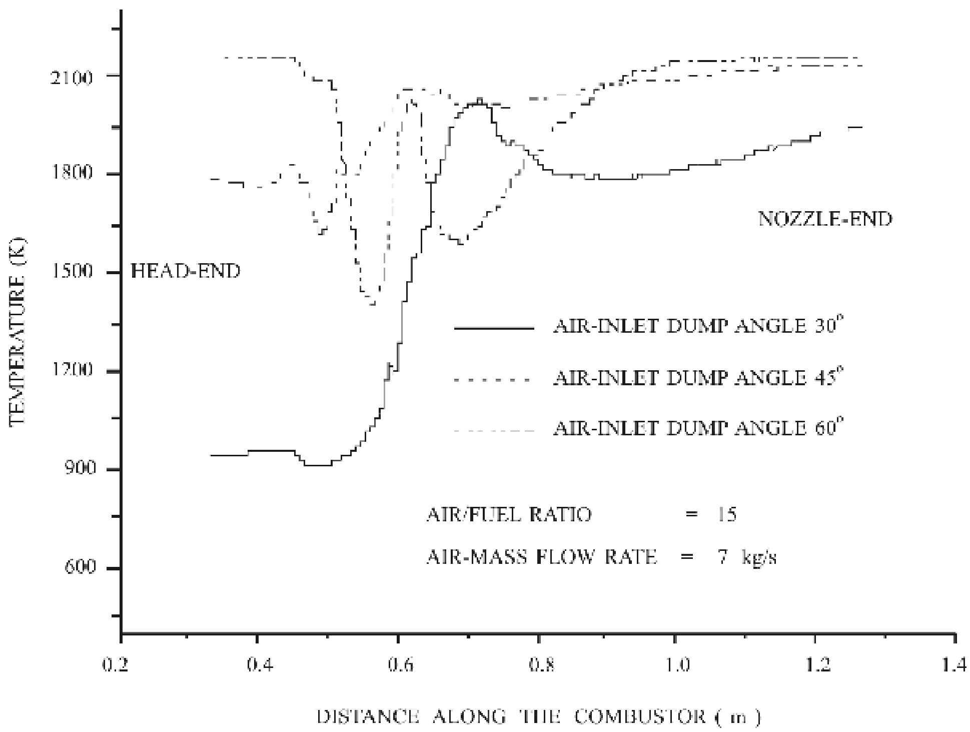

Figure 6. Effect of air-inlet dump angle on centreline variations of temperature.

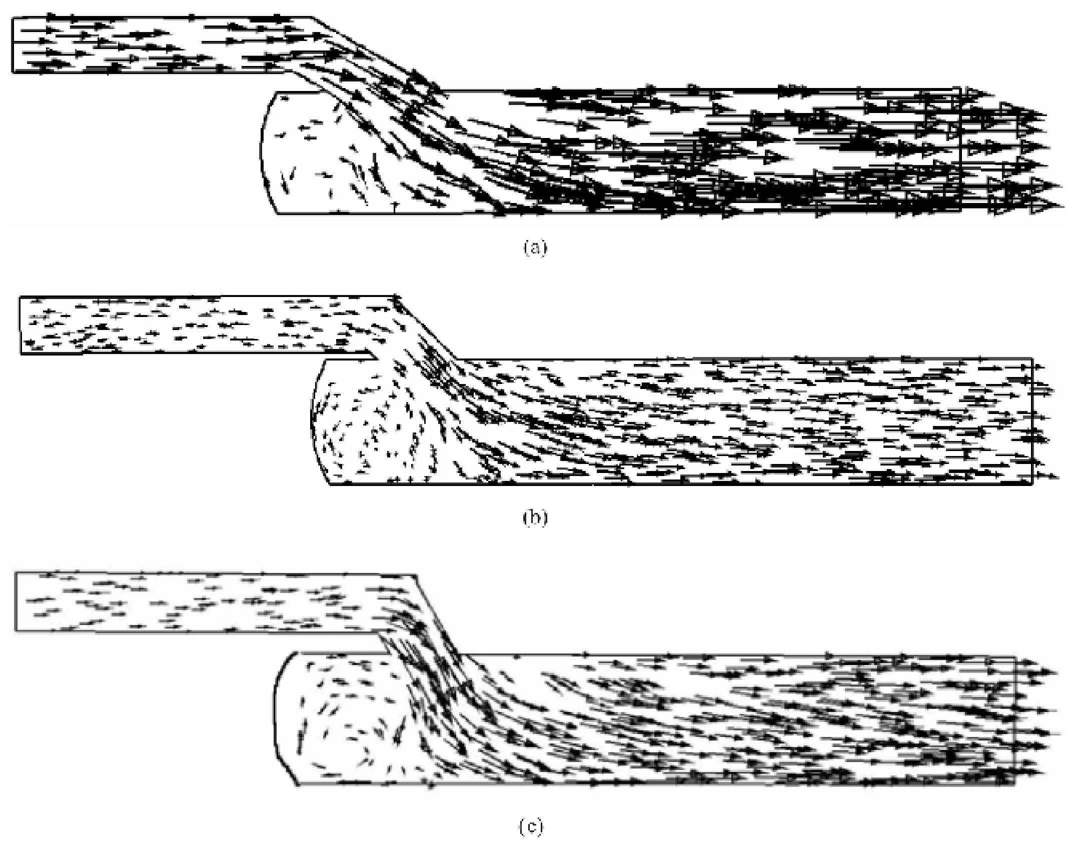

Figure 7. Velocity vectors for different air-inlet dump angles: (a) 30º, (b) 45º, and (c) 60º.

of mass fraction of CO_2 shown in Fig. 9 indicate the extent and completeness of combustion.

4.4.2 *Effect of Air/Fuel Ratio*

Temperature along the centreline of the combustor for different air/fuel ratios for a dump angle of 45° is shown in Fig.10. The temperature profile is quite sensitive to the air/fuel ratio. For the rich and stoichiometric cases, combustion reactions occur mostly downstream of the air inlet. Here, the diffusion of air and fuel plays an important role. For air-fuel ratio of 30, most of the combustion process is completed in the recirculation region at the head-end, as an aerodynamically-stabilised flame.

4.4.3 *Effect of Droplet Size*

Three different mean droplet sizes, namely 20 mm, 50 mm and 100 mm have been considered and the corresponding predictions are plotted in Fig. 11.

This figure clearly illustrates that small droplets (20 mm) tend to evaporate completely in the inlet region itself and hence combustion reactions are almost completed near the inlet.On the other hand, larger droplets disperse deeper into the combustor and take longer to evaporate. The evolution of the temperature field with axial distance is slower for the case with large-sized droplets. However, the

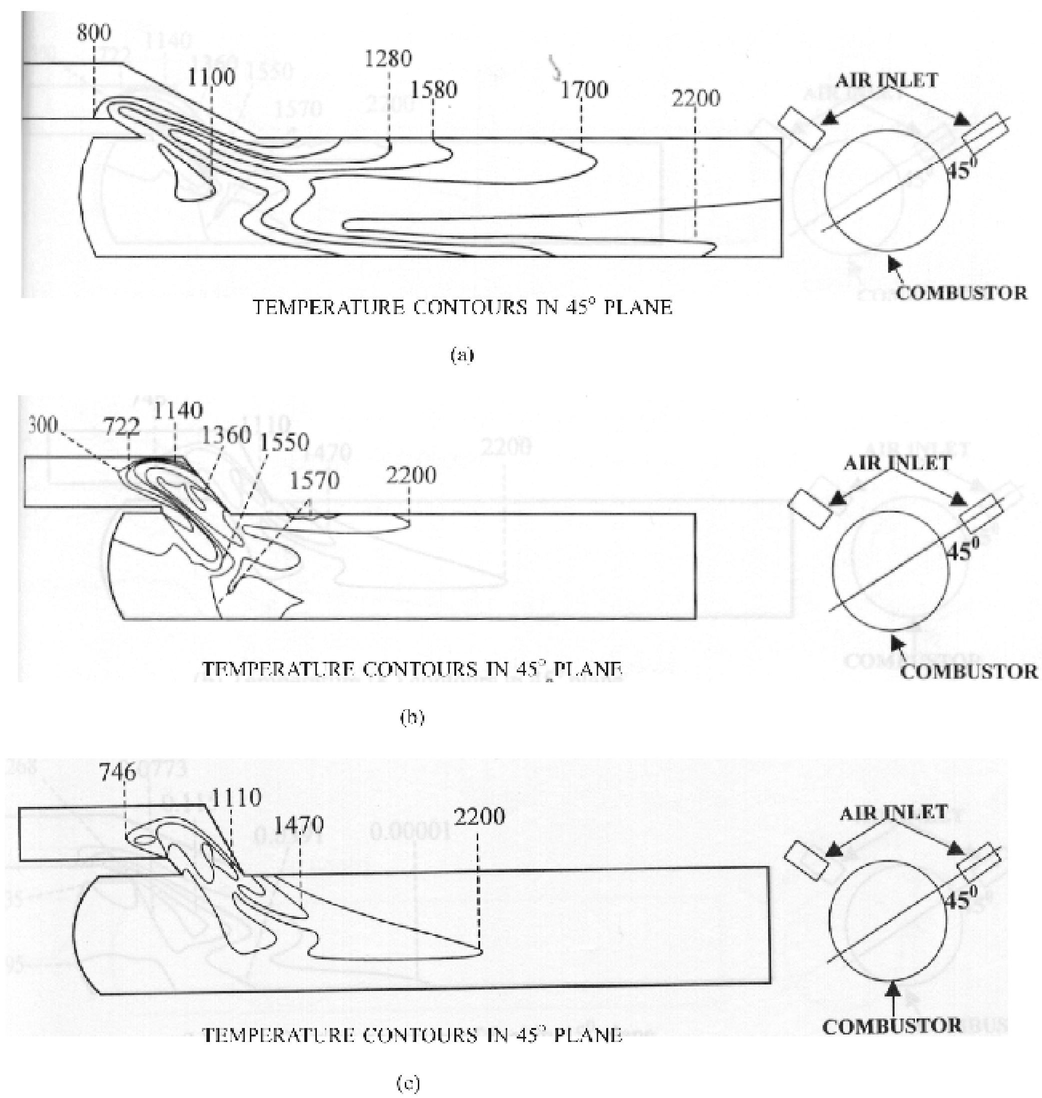

Figure 8. Temperature contours for different air-inlet dump angles: (a) 30°, (b) 45°, and (c) 60°.

larger droplets tend to attain the adiabatic flame temperature (2260K) compared to the smaller-sized droplets.

5. CONCLUSIONS

The numerical predictions of a two-side-inlet (90° apart) dump combustor are validated with the experimental data generated at the Liquid Ramjet Combustor Test Facility. The predictions show a fairly good agreement with the limited experimental data available. The important conclusions arrived through are given below:

- Parameters such as the air-inlet dump angle, air/fuel ratio and size of fuel droplets have significant influence on ramjet combustion.
- For each dump angle, the static pressure increases from the head-end up to the point of impingement of the side-air jets and then it decreases with increase in axial distance. At the jet impingement location, peak value of static pressure is obtained due to stagnation condition for the flow. Beyond this point, the flow reaccelerates and fills the whole cross section of the combustor. Therefore, the static pressure decreases with axial distance, beyond the impingement point.

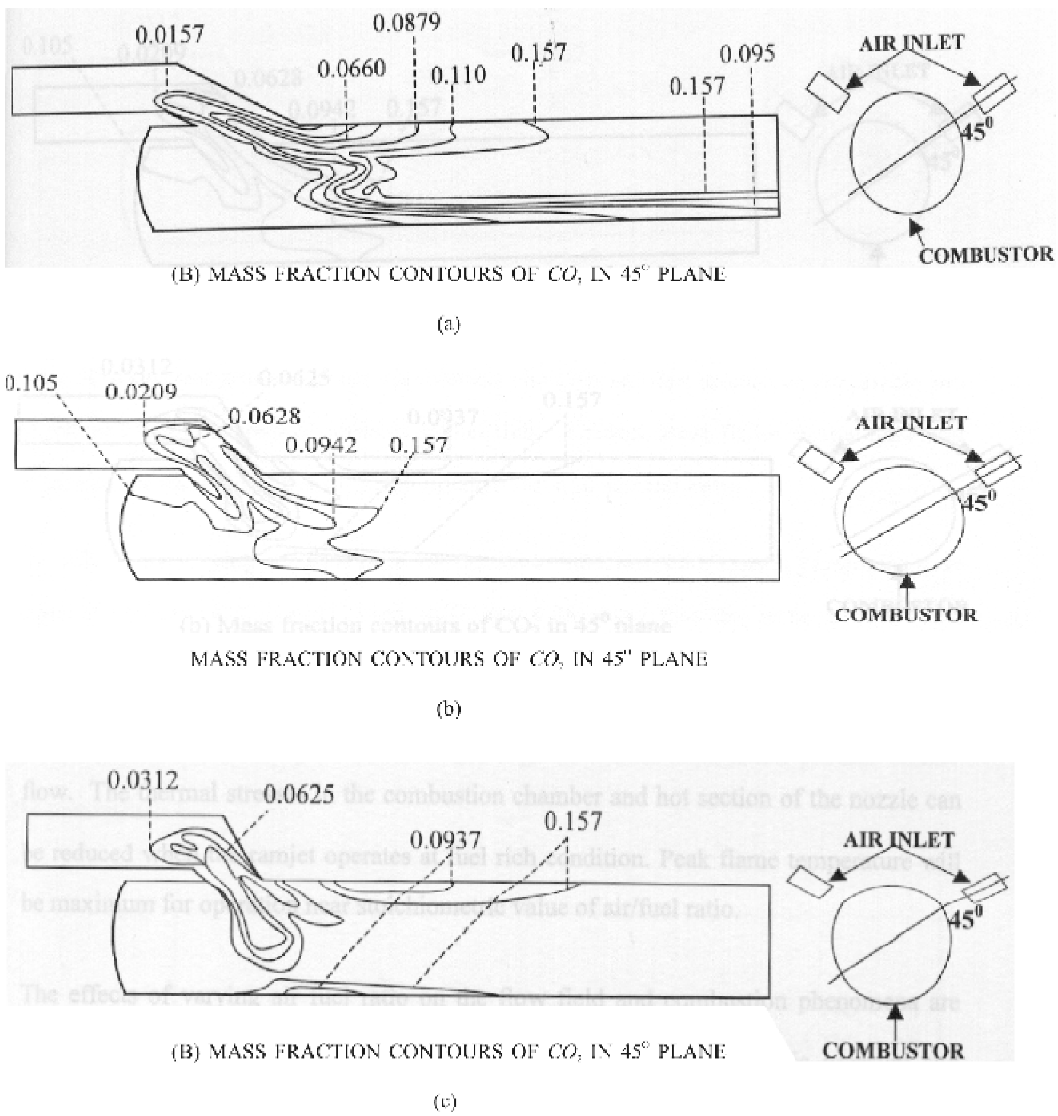

Figure 9. Mass fraction contours of CO_2 for different air-inlet dump angles: (a) 30°, (b) 45°, and (c) 60°.

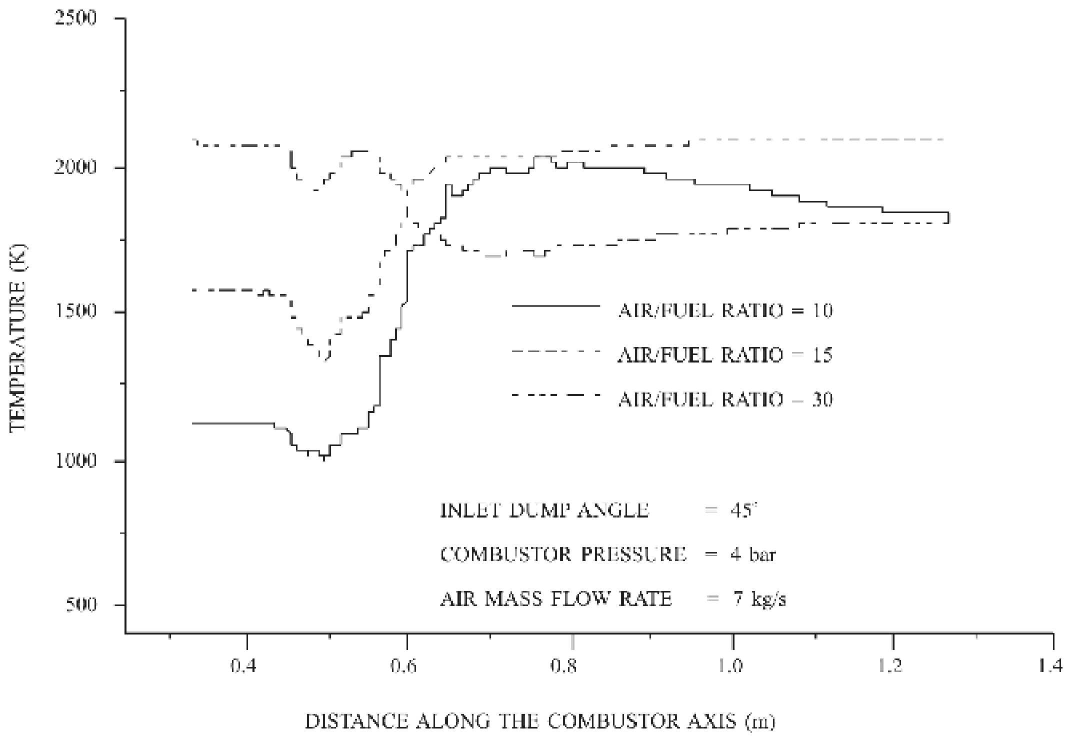

Figure 10. Effect of air/fuel ratio on centreline variations of temperature.

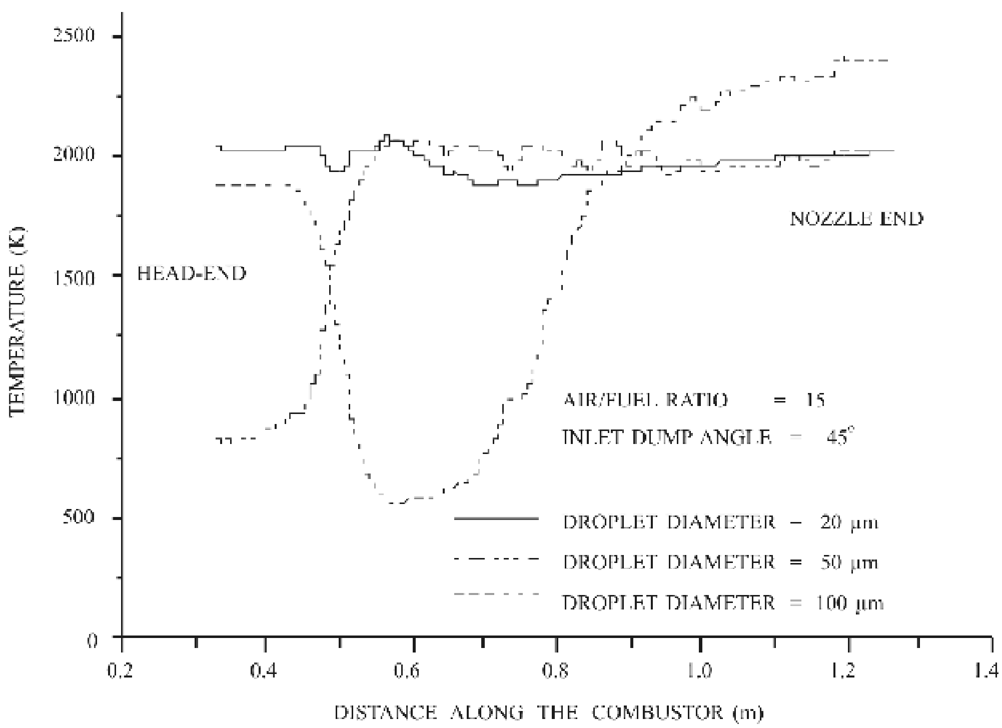

Figure 11. Effect of fuel droplet size on centreline variations of temperature.

The jet impingement location moves closer to that head-end of the combustor with an increase in dump angle. Before the jet impingement point, axial velocity values are small and negative in magnitude, indicating the presence of a recirculation zone between the two air-jets close to the head-end. Due to the presence of stronger recirculation at a high dump angle, it is seen that the temperature in the head-end region increases. However, there is a dip in temperature near the point of impingement of the jets due to the mixing of cold air in this region. At larger axial distance again, due to better mixing between the hot and the cold gases, combustion attains completion and the local temperature value becomes close to the adiabatic flame temperature.

Air-inlet dump angle influences the size and strength of the recirculation zones formed. The size of recirculation zone decreases with increase in dump angle (since jet merger point moves closer to the head-end), but the strength of recirculation increases. Due to the presence of stronger recirculation at a high dump angle, it is seen that the temperature in the head-end region increases. For a dump angle of 30°, it is seen that the recirculation zone at the head-end region is not very effective in its flame-holding action and hence temperature values are relatively lower as compared to the cases with dump angles of 45° and 60°. Combustion process completes at a shorter distance from the air inlet for the dump angles of 45° and 60°, while a longer distance is required for the 30° case.

The static pressure and axial velocity along the centreline of the combustor do not vary much with air/fuel ratio and the results for rich as well as lean mixture are quite similar to the stoichiometric case. However, the temperature profile is quite sensitive to the air/ fuel ratio. Combustion is sustained by the recirculation pattern in the rich (A/F = 10) case, while a longer length is needed for combustion in the case of A/F = 15 and 30.

For fuel droplets with 20 μm diameter, the deviation from the peak temperature is minimal, whereas introducing particles with 50 μm and 100 μm result in considerable variations of the temperature along the combustor axis.

The flow model developed here provides the capability to evaluate different designs for obtaining a satisfactory fuel distribution pattern.

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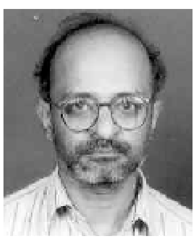

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