Analysis of Supersonic Combustors with Swept Ramp Injectors

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Introduction

THE design of an efficient scramjet combustor has proven to be difficult, partly because of the structural limitations caused by high heat transfer rates and short residence times for fuel and air mixing. A large portion of the design phase of these combustors will rely heavily on computational fluid dynamics because of difficulties in mimicking scramjet conditions at ground test facilities. Therefore, it is imperative that algorithms be developed that encompass as much of the flow physics as possible. Some of the areas that need to be addressed include turbulence modeling, turbulence–chemistry interactions, and accounting for variable turbulent Prandtl and Schmidt numbers. Most of the effort of this work has been devoted to issues involved with the turbulence modeling and turbulence–chemistry interactions.

Calculations of an experimental swept ramp combustor geometry[1,2] have been performed. The design of this combustor allows for nearly parallel injection of the fuel that enhances the available thrust of the engine and reduces shock losses when compared to combustors that inject the fuel normal to the airflow. Mixing is enhanced through the creation of streamwise vorticity by two mechanisms. Vorticity is first created as the high-pressure flow above the ramps spills over to the low-pressure region between the ramps. This spillage is further enhanced by adding spanwise sweep to the ramps. Downstream of the ramps, vorticity is generated through the baroclinic torque mechanism by the interaction of oblique shocks with the injected fuel. Experimental measurements include Mie scattering flow visualization, wall pressure profiles, wall heat transfer rates, and pitot pressure surveys.

Computational results for this geometry have previously been presented by Eklund and Stouffer.[3] Their calculations invoked a two-zone algebraic turbulence model to account for the velocity fluctuations, and no attempt was made to allow for turbulence–chemistry interactions. Their computations compared well with pressure measurements, however, heat transfer rates were consistently underpredicted when compared with experiment. The present work revisits this experiment to examine the effects of using a more elaborate two-equation (k-ω)[4] turbulence model, as well as accounting for the turbulence–chemistry interactions using probability density functions (PDFs).

Results and Discussion

Details of the calculations and other results that could not be included in this Note are given in Ref. 5. In all of the figures, G is the gap length defined as twice the combustor entrance height. Figure 1 compares the wall pressure profiles along the bottom and top walls at the centerline between adjacent ramps. The PDF employed had a negligible impact on the wall pressure, and so calculations with the PDF are not included in this figure. Overall, the predictions compare well with the experiment. The sharp pressure rise just downstream of the ramps is caused by the interaction of the reflected ramp shock with the combustion front. In this region the computational predictions show a complicated shock structure that quickly decays because of viscous effects and heat release as a result of combustion. Downstream of this region, the pressure field drops monotonically as the flow enters the diverging section of the combustor, and the computed results mimic the experimental data quite well.

Wall heat transfer comparisons are shown in Fig. 2. Comparisons are shown along the top and bottom walls at the centerline between adjacent ramps. Two methods were used to obtain the experimental wall heat transfer rates. The first method obtained the heat transfer rates indirectly from wall temperature histories measured by surface thermocouples. The second method used Gardon gauges. As with the wall pressure profiles, the computed heat transfer rates show a jagged shape near the combustion front. Downstream of this region, the profiles are consistently underpredicting the heat transfer rates. This same trend occurred in the calculations of Eklund and Stouffer[3] using a two-zone algebraic turbulence model. Accounting for the turbulence–chemistry interactions did little to improve the comparisons. The first grid point off the wall for this region in the present calculation corresponds to a z^+ of about 1.0. Although further grid refinement might show some improvements, it is doubtful that this would explain such a large discrepancy. A more likely explanation may lie in the assumption of a constant turbulent Prandtl number. Several authors[6,7] have pointed out the need for allowing the Prandtl number to vary in compressible turbulent flowfields, especially when trying to predict heat transfer rates. To examine the importance of an appropriate choice of turbulent Prandtl and Schmidt numbers, a third set of calculations was carried out with a reduced turbulent Prandtl number while keeping the turbulent Lewis number as 1.0. As expected, reducing the turbulent Prandtl number (which enhances the heat diffusion), increased the heat transfer to the walls.

Figure 3 compares the pitot pressure profile at an X/G of 14.1 along the symmetry line present between two adjacent ramps. Also shown in this figure are the computational results of Eklund and Stouffer,[3] where the turbulent Prandtl and Schmidt numbers were set to 0.9 and 0.5, respectively. The

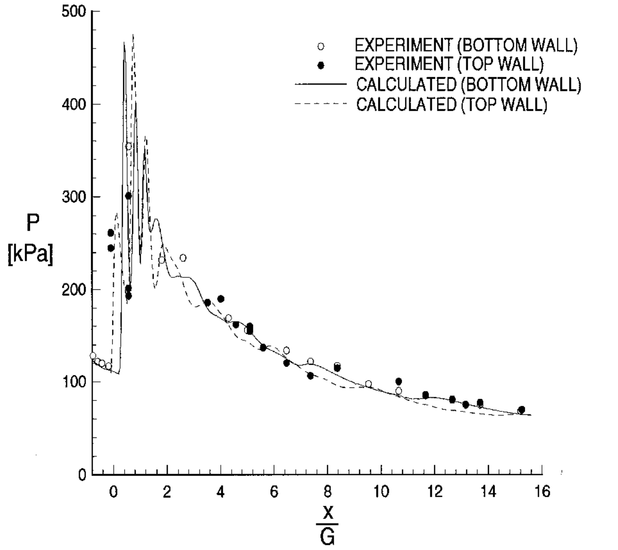

Fig. 1 Wall pressure comparison with experiment at the interstice centerline.

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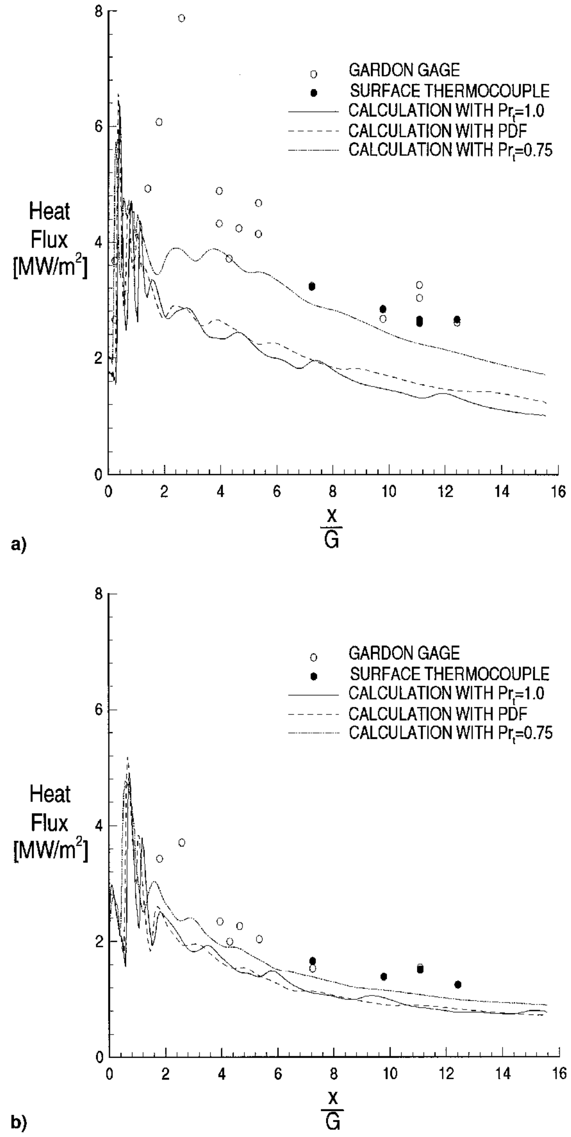

Fig. 2 Heat transfer rate comparison with experiment at the interstice centerline: a) lower and b) upper walls.

calculation with a turbulent Prandtl number of 1.0 agrees well with experimental data near the top wall of the combustor (outside the combustion zone), but significantly overpredicts the pitot pressure near the bottom of the combustor. The calculation with the reduced turbulent Prandtl number showed vast improvements in regions of significant combustion, but underpredicted the total pressure outside of the combustion zone.

Concluding Remarks

In conclusion, the use of the PDF did not yield any significant improvements over treating the chemical source terms in a laminar fashion. The calculations compared well with available wall pressure data and Mie flow visualization, however, heat transfer rates were consistently underpredicted. Further study is needed to deal with the effects of variable turbulent Prandtl and Schmidt numbers. The instream pitot pressure survey comparisons offered further evidence to the importance of proper specification of turbulent Prandtl and Schmidt numbers for these flows.

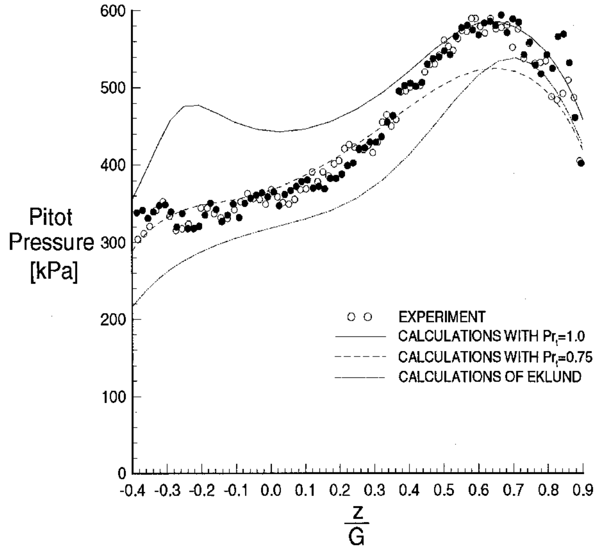

Fig. 3 Pitot pressure survey comparison with experiment.

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