COMPUTATIONAL ANALYSIS OF THERMAL COMPRESSION EFFECTS IN A SUPERSONIC INLET

Richard G. Haws
Department of Mechanical Engineering
Brigham Young University
Provo, Utah

Abstract

The inlet area contraction ratio of a scramjet engine is one of the most important parameters in determining engine performance. A thermal compression inlet is studied in which one surface of an internal-external compression inlet is replaced by a high-pressure jet of combustion gases. The inlet flowfield is calculated using a two-dimensional computer model. The thermal compression inlet is shown to eliminate the boundary layer-shock wave interaction which normally limits inlet contraction ratios of the internal-external compression inlets used at high flight Mach numbers. In addition, studies suggest that the level of compression can be controlled by varying the pressure of the compression jet.

Introduction

Advances in military flight technology and increases in the demand for space flights to deploy satellites have led to a need for efficient, low-cost engines which can power vehicles flying at very high speeds. Air-breathing engines are among the most efficient engines, and hold much promise for the future. One experimental air-breathing engine, called the scramjet engine, has been the subject of much research. This paper addresses the need for a light-weight, efficient scramjet inlet.

The performance of an air-breathing engine depends in part on the pressure at which heat is added to the air flow by fuel combustion. An effective inlet to an air-breathing engine will cause a high pressure rise in the incoming air without restricting the flow through the engine. In a scramjet engine, this compression is accomplished by using a converging-area inlet. A high inlet area contraction ratio causes a large pressure rise; however, the contraction ratio is limited. At a given flight Mach number, there is a maximum contraction ratio which will not cause inlet "spill-over," a condition in which some of the air flows around the engine instead of flowing through it. Since the thrust produced by an engine is proportional to the mass flow through the engine, spill-over decreases the thrust produced by the engine.

Another limitation on the inlet contraction ratio arises when the inlet employs some internal compression. Internal compression refers to the presence of a shock wave internal to the inlet, and must be used at high supersonic Mach numbers. The contraction ratio is limited by the interaction of the internal shock wave with the boundary layer which forms along the inlet wall. If the pressure rise across the shock wave is too high, this interaction will cause the boundary layer to separate from the surface. When this happens, the flow through the engine is completely blocked. This condition is called engine unstart, and it is much more serious than spill-over because an unstarted engine produces zero thrust.

For a vehicle operating over a wide range of speeds, the optimum inlet area contraction ratio will vary significantly depending on flight Mach number. Therefore, in order to produce maximum thrust, engines are typically equipped with variable-geometry inlets. The extra weight and cost of a variable geometry engine, however, make it desirable to develop an efficient inlet which can operate with little change in geometry. In 1973, Antonio Ferri suggested using the pressure rise caused by heat addition in one zone to compress the air entering other combustion zones[1, 2]. This concept is known as thermal compression.

One method of employing thermal compression was proposed several decades ago in which heat addition was distributed in two combustion zones. Computations using one-dimensional models showed that the thrust per kilogram of fuel produced by a fixed-geometry scramjet engine was increased by up to 61% using this type of thermal compression[3]. The method was later studied using two-dimensional models in which this large increase in specific impulse was verified[4, 5]. It was found, however, that this engine concept would be difficult to implement without some variable geometry, and that the location of heat addition would have to be carefully controlled. Controlling the heat addition precisely would be difficult because the combustion process depends on the mixing of fuel and air.

The present work will focus on a different implementation of the thermal compression concept. The thermal compression inlet referred to in this work uses a high-pressure jet to cause the first oblique shock in the inlet. Because this jet is used instead of a physical wall, boundary layer-shock wave interactions do not limit the contraction ratio. The purpose of the current work is to demonstrate the thermal compression inlet in a computational model and to investigate the flowfield characteristics through a two-dimensional numerical model.

Model Description

Fig. 1 shows the thermal compression inlet and the region included in the computational model. Fig. 1a is a schematic of a fixed-geometry scramjet engine with a two-shock, internal-external compression inlet. In Fig. 1b the first compression ramp has been replaced by a stream of high-pressure exhaust gases, which we will call a compression jet, coming from an upstream combustion process. The virtual surface created by the compression jet ends at a splitter plate which separates the jet from the inlet air stream. After fuel is burned in the upper stream, both streams are expanded in a nozzle, producing thrust. By using the thermal compression inlet, the problem of the internal shock wave meeting a boundary layer is eliminated, which increases the maximum contraction ratio achievable without engine unstart. It is also expected that the shock positions can be controlled by varying the pressure in the compression jet, eliminating much of the need for a variable-geometry inlet. The pressure of the compression jet can be controlled by the combustion process used to produce the compression jet. In the current work we study the flow details of the thermal compression inlet at a single Mach number. The pressure of the compression jet is chosen equal to the pressure of the inlet air after the initial shock wave, as predicted by compressible flow theory. The ability to set up the desired shock wave by matching pressures provides an initial validation of the ability to control the shock location by varying the pressure of the compression jet. The computational domain (Fig. 1b) begins upstream of the point where the two streams join and extends downstream of the leading edge of the splitter plate.

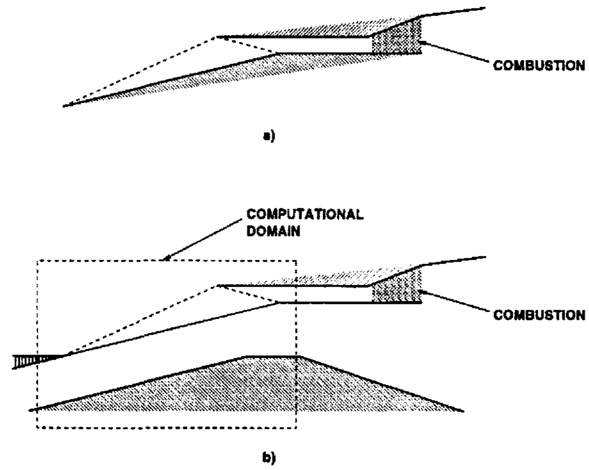

Figure 1: Schematic of (a) standard inlet and (b) thermal compression inlet.

Solution Method

Modeling of the thermal compression inlet is accomplished using a computer program that solves the Navier-Stokes equations which govern fluid flow using a diagonalized, upwind-biased solution scheme[6, 7]. Free-stream conditions are obtained using a representative trajectory, and the inlet conditions assume a bow shock off the fore-body of the vehicle. The program includes the effects of viscous walls and turbulence, and the compression jet is assumed to be air.

Results

The calculated flowfield shows the feasibility of replacing the first compression surface with a high-pressure jet. Fig. 2 shows a contour plot of the pressure field in the thermal compression inlet at a free-stream Mach number of 6.0. The flow in the upper streamtube enters at inlet conditions. When this flow meets the high-pressure compression jet, it is turned and compressed as though it had met an inlet wall, causing an oblique shock to form. Since the pressure in the lower jet closely matches the pressure in the upper streamtube after the shock, the lower streamtube is largely unaffected. As can be seen in the streamlines and horizontal-velocity contours in Fig. 3, a streamline separates the captured inlet air from the incoming jet, and virtually all of the inlet air enters the region above the splitter plate.

One advantage of the thermal compression inlet is seen in the absence of a boundary layer in the inlet flow immediately upstream of the splitter plate. This is demonstrated in Fig. 4, showing the velocity vectors just upstream of the leading edge of the splitter plate. The absence of a boundary layer eliminates the boundary layer-shock wave interaction which normally limits the contraction ratio of internal-compression inlets. By locating the splitter plate so that the second shock wave just misses the leading edge of the splitter plate, the thermal compression inlet avoids any interaction of the shock wave with even the small boundary layer forming at the beginning of the splitter plate.

Future Work

The results presented herein provide a foundation for further research which will provide more specific estimates of the performance increase which can be achieved through the use of the thermal compression inlet. This research will model inlets with various area contraction ratios to determine the maximum contraction ratio achievable with the thermal compression inlet at various Mach numbers. These will be compared with contraction ratios achieved without thermal compression. It will also investigate the degree to which the inlet compression can be controlled and varied with the thermal compression inlet. These efforts will include the use of solution-adapted grids to better resolve shock waves in the calculated solution. Furthermore, by extending the computational domain to include the exit nozzle, specific impulse will be estimated.

Conclusions

In a scramjet inlet employing internal compression, the area contraction ratio is limited by the interaction of the shock wave with the boundary layer forming along the wall. At high contraction ratios, this interaction can lead to boundary layer separation and engine unstart. A thermal compression inlet is proposed for a two-shock, mixed-compression inlet in which the compression ramp is replaced by a jet of high-pressure combustion gases. The thermal compression inlet has the advantage that there is no wall to cause a boundary layer which will interact with the internal shock wave. Numerical calculations have shown that the first compression surface in a mixed compression inlet can indeed be replaced by a high-pressure jet at the appropriate pressure. It is shown that this replacement eliminates the boundary layer interaction with the second shock; therefore, it is expected that the thermal compression inlet will be able to deliver higher compression ratios at high Mach numbers than have been previously achieved. A further advantage of the thermal compression inlet is the ability to control the location of the initial shock wave by controlling the pressure of the compression jet. Further work is needed to investigate the effects of varying the compression jet pressure at several flight Mach numbers with the goal of achieving optimum compression in the inlet.

References

[1] Ferri, A., "Mixing-Controlled Supersonic Combustion," *Annual Review of Fluid Mechanics*, vol. 5, 1973, pp. 301–38.

[2] Curran, E. T., Heiser, W. H., and Pratt, D. T., "Fluid Phenomena in Scramjet Combustion Systems," *Annual Review of Fluid Mechanics*, vol. 28, 1996, pp. 323–60.

[3] Billig, F. S., Orth, R. C., and Lasky, M., "Effects of Thermal Compression on the Performance Estimates of Hypersonic Ramjets," *Journal of Spacecraft*, vol. 5, no. 9, September 1968, pp. 1076–81.

[4] Haws, R. G., and Daines, R. L., "Computational Analysis of Spatially-Distributed Thermal Compression Effects in Supersonic Flowfields," AIAA Paper 98-0931, 1998.

[5] Billig, F. S., "Two-Dimensional Model for Thermal Compression," *Journal of Spacecraft and Rockets*, vol. 9, no. 9, September 1972, pp. 702–3.

[6] Pulliam, T. H., and Chaussee, D. S., "A Diagonal Form of an Implicit Approximate-Factorization algorithm," *Journal of Computational Physics*, vol. 39, 1981, pp. 347–63.

[7] Buelow, P. E. O., Schwer, J. F., and Merkle, C. L., "A Preconditioned, Dual-Time, Diagonalized ADI Scheme for Unsteady Computations," AIAA Paper 97-2101, 1997.

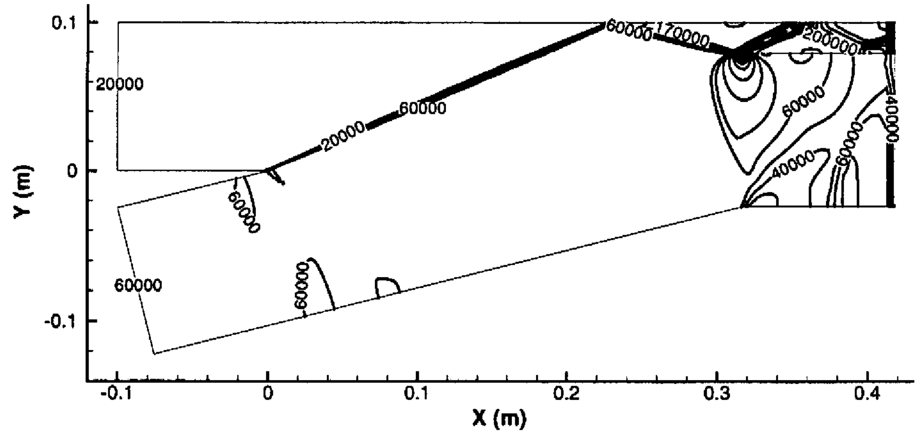

Figure 2: Pressure contours for the thermal compression inlet, Mach 6 free stream.

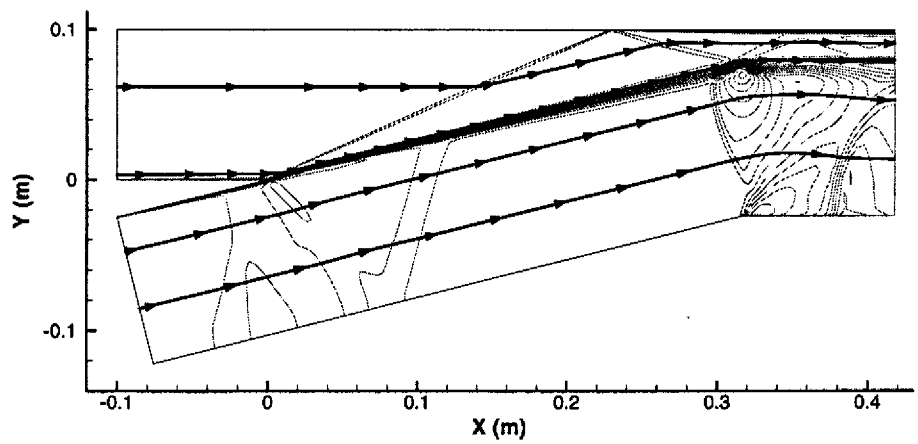

Figure 3: Streamlines and Horizontal-velocity contours for the thermal compression inlet, Mach 6 free stream.

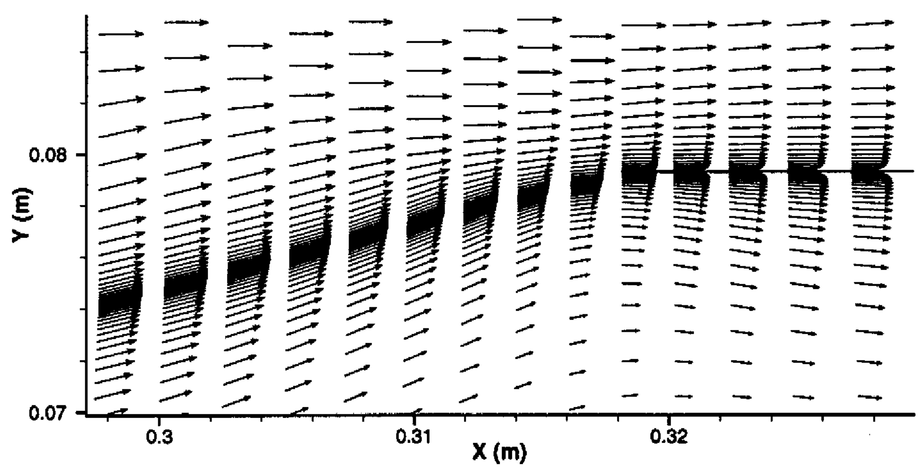

Figure 4: Velocity vectors near leading edge of splitter plate.