16th Australasian Fluid Mechanics Conference:
Design of a captive carry Mach 1.8 ramjet

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Abstract

There are various fluid mechanics problems which need to be considered, both internally and externally during the flight of a ramjet. During the design and subsequent launch of our Mach 1.8 ramjet, several issues were investigated such as the formation, position and importance of shockwaves within the ramjet, design of a flame holder to encourage required flow recirculation within the combustion chamber, flow associated with the delivery of liquid fuel, and the effect of outer profile on external drag. In addition to these fluid mechanics problem, the theoretical and practical considerations of making ramjets work and present flight data are discussed.

Introduction

As our final year group design project, we designed, fabricated and launched a captive carry Mach 1.8 ramjet (as shown in Figure 1) in Woomera as the payload of a Zuni rocket as part of the Australian Space Research Institute's Small Sounding Rocket Program. The Zuni rocket contained a recoverable instrumentation payload which was used to monitor performance. This project was conducted under the Mechanical and Space Engineering program at the University of Queensland and was aimed at giving project based learning experiences to undergraduate students.

Ramjets, which are a form of air-breathing propulsion, have the potential to be used as an intermediate propulsion phase between the slower turbojets and faster scramjets thus are of much benefit to ongoing scramjet research.

Design issues and choice of parts

The configuration of the launch was such that our ramjet was attached to a Zuni rocket motor and accelerated up to the desired operational velocity of Mach 1.8. At this time the Zuni would stop firing and the ramjet would engage. The predicted thrust of the ramjet was enough to overcome the drag forces of the Zuni/ramjet, and therefore it was important to ensure our design could operate effectively over a range of velocities.

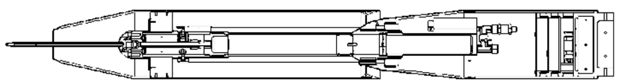

Figure 1: Cross-section of the entire ramjet.

Pitot inlet

In general, pitot inlets are the least efficient of all the types of air-breathing propulsion inlets, however the difference in efficiency at low supersonic speeds such as Mach 1.8 is not significant. Efficiency is quantified in terms of the amount of pressure recovery across the inlet. For a pitot inlet, the pressure recovery is simply the pressure recovery across a normal shock, since this is the only shockwave which forms in a pitot inlet. Furthermore, pitot inlets can successfully operate over a range of velocities which made them favourable for our ramjet.

Nozzle

The nozzle was required to accelerate the flow from a subsonic speed exiting the combustion chamber to a supersonic speed exiting the aircraft. For the flight conditions our ramjet required a converging diverging nozzle to produce supersonic exhaust flow. Due to the captive carry design constraint, an annular nozzle was used to direct flow around the outside of the vehicle. The main design criteria were to choke the flow at the throat and correctly expand the flow to the design conditions in a direction as close to axial as possible. The nozzle had a rounded throat to reduce internal shockwaves during expansion.

Flame holder

The flame holder provides flame stabilization by inducing turbulence into the flow which produces both recirculation and mixing regions. As gas flows past the flame holder, a large portion of it would travel through these recirculation and mixing zones indicated in Figure 2, which increase the residence time of the gas. Hence placing the source of ignition within these regions where the residence time is higher would increase the chance that flame stabilization will occur.

Having the longest residence time or largest areas of recirculation and mixing produces the best conditions for flame stabilization. For a particular flow and geometry of flame holder, the residence time is proportional to the blockage ratio: the ratio of cross sectional area of the flame holder to flow. This parameter is limited in that the flame holder must not be so large that it will choke the flow.

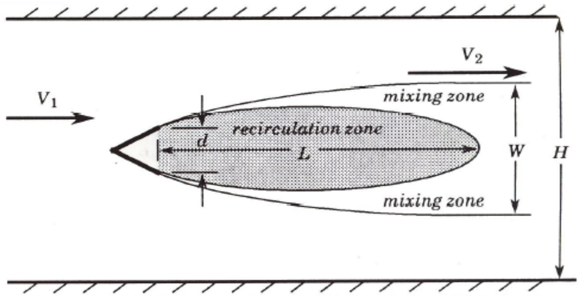

Figure 2: Dimensions used in flame-holder design [7]

Pitot Tube

To obtain data from the flight a pitot-static tube was used for measuring total and static pressure. It protruded from the front of the ramjet intake so that free stream conditions could be measured. Therefore it was important that the conditions at the inlet were disturbed by the shock waves created by the Pitot tube.

Design approach

Ramjets use shockwave phenomena to compress the air flowing into the combustion chamber instead of using a compressor like a gas turbine engine. This also eliminates the need for a turbine allowing the air to flow through the ramjet without many significant obstructions.

The function of the pitot inlet in the ramjet is to induce a single normal shockwave across which the static pressure is raised. Knowing the behaviour of the shockwave at various flight conditions as well as specifying the geometry of the ramjet affects the conditions at the entry to the combustion chamber. These conditions such as temperature, pressure and flow speed are critical to determining whether the spark energy input is sufficient to successfully ignite the fuel-air mixture.

Flow Analysis

Based on previous launch data the expected flight test conditions are Mach 1.8 at an altitude of 1 km. The constraints on the flow are that a normal shock occurs at the front or inside the pitot inlet; the flow is choked at the nozzle and the flow exiting the nozzle is correctly expanded. For favourable combustion of iso-octane the stoichiometric air-fuel ratio is 15:1, therefore based on a fuel flow rate of 0.1 kg/s the mass flow rate of air was assumed to be 1.5 kg/s. Assumptions include calorically perfect gas, frictionless flow and no heat loss.

The area ratios required to satisfy the constraints above can be found using isentropic flow and normal shock relations. Although effects of the heat addition to the flow can found using Rayleigh flow relations, NASA's Chemical Equilibrium and Applications (CEA) program [4] was used for increased accuracy in determining the final temperature of the combusted fuel-air mixture.

Preliminary Design Method

Based on the altitude, design flight Mach number and an air mass flow rate of 1.5 kg/s the pitot inlet area was found. It was then assumed that for design conditions the shock occurs exactly at the front of the pitot inlet. This assumption allows determination of the downstream conditions of the flow.

The flow behind the normal shock is subsonic and expands into the combustion chamber. Associated with the expansion of a subsonic flow are increases in pressure and temperature and a decrease in flow velocity, all of which are optimal for combustion. For this reason the combustion chamber diameter was made the same as the Zuni rocket as this would provide maximum expansion of the flow.

Before entering the combustion chamber iso-octane is injected into the air flow which is then combusted behind the flame holders providing the heat addition to the flow, necessary for thrust. As mentioned before, this heat addition process was modelled by CEA and along with further analysis the flow properties at the exit of the combustion chamber were determined.

Knowing the conditions at the exit of the combustion chamber allowed the selection of a combustion chamber to nozzle throat area ratio that causes the subsonic flow to accelerate to Mach 1. The flow becomes supersonic after the nozzle throat. Expanding a supersonic flow decreases its pressure so a throat area was selected such that the flow would be correctly expanded.

Non-Ideal Combustion Conditions

The main goal of the project was to generate combustion inside the ramjet therefore it was important to know whether the off-design conditions provided suitable temperature, pressure and equivalence ratio for combustion. Under design conditions all the constraints mentioned in the flow analysis are satisfied however when the flight Mach number and altitude deviates from the design conditions the combustion of the fuel-air mixture as well as the ramjet's performance is affected.

Performance is dependent on the altitude and flight Mach number as these affect the properties of the shockwave compressing the flow as well as the equivalence ratio for combustion. The equivalence ratio affects the heat addition to the flow and associated with the shock is a total pressure loss. From calculations it was found that the equivalence ratio of combustion and the position of the shock are coupled as shown in Figure 3. Note that a positive increase in distance is oriented towards the rear of the ramjet.

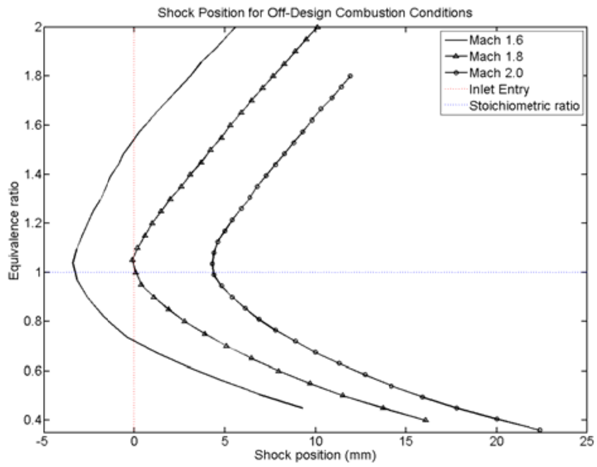

Figure 3: Shock position for off-design combustion conditions

The results seen in Figure 3 are purely theoretical however they are indicators as to how the shock may behave for various off-design conditions. It can be seen that for increasing flight Mach number and combustion at equivalence ratios away from stoichiometric, forces the shock inside the inlet. Equivalence ratios for iso-octane that are less than 0.5 are inflammable [6].

Increasing flight Mach number increases the mass flow rate of air entering the combustion chamber. Since the fuel injection rate is independent of the flow rate of air, the increase in air mass flow rate reduces the temperature of the flow exiting combustion chamber since more air has to be heated by combustion. A reduction in temperature allows more air to flow through the nozzle throat decreasing the combustion chamber pressure which allows the shock to move inside the inlet, as there is less back pressure pushing the shock outwards.

The supersonic flow entering the pitot inlet sees an increasing area ratio, thereby expanding the flow and increasing its Mach number. From normal shock relations it can be understood that shocks occurring at increasing Mach numbers involve a greater loss of total pressure, potentially reducing the static pressure available for combustion.

For decreasing flight Mach numbers and roughly stoichiometric combustion ratios the shock moves off the front of the inlet. In this case the back pressure from the combustion chamber forces the shock off the front of the inlet and causing air to spill around the outside, reducing the mass flow rate of air into the ramjet.

When the ramjet is not combusting there is no heat addition to the flow. This effectively results in a lowered combustion chamber pressure allowing the shock to move deeper inside the inlet as a result of lower back pressure. The flow in front of the shock in the non-combustion case at design conditions is almost Mach 3. A normal shock at Mach 3 has a 65% loss in total pressure. In comparison to the combustion case, the normal shock occurs at Mach 1.8 having a much lower total pressure loss of 19%. Despite the large loss in total pressure in the non-combustion case the spark energy input is still sufficient to ignite the fuel-air mixture initiating the transition from non-combustion to sustained combustion.

CFD Analysis

Computational Fluid Dynamics (CFD) was used to simulate the flow conditions expected throughout the ramjet and to verify our design, of which the critical dimensions were determined from the theory as discussed in previous sections. The simulations were performed using two different programs; MBCNS [5], written by Dr Peter Jacobs of the University of Queensland, and the commercially available ESI-FASTRAN [2]. Since the ramjet is axisymmetric, 2D CFD simulations were used.

As flight conditions would be constantly changing, it was important to not only simulate desired on-design conditions, but also to consider a wide range of possible off design conditions. In particular, we investigated velocities above and below the Mach 1.8 on-design velocity, with varying levels of heat addition (which result from the non-constant fuel delivery rate).

The things we wanted to check for were most importantly if combustion could occur at the aforementioned off-design conditions, and if so, the flow conditions and resulting efficiency.

CFD – No combustion

All non-combustion simulations were set up as a transient problem with the ramjet initially at rest and being instantaneously accelerated to the desired free stream velocity. The simulations were set up in this way because the solvers tended to run into problems when the conditions at the outlet were subsonic, an erroneous solution would be propagated from the outlet, upstream. Instead of gradually increasing the velocity up to Mach 1.8 (as would occur in the actual launch), the inlet velocity was applied in this instantaneous fashion to avoid the subsonic boundaries wherever possible.

Figure 4 and Figure 5 which were computed using MBCNS, show the velocity and temperature profiles for the steady solution at the desired velocity of Mach 1.8. These are the expected conditions just before fuel would be delivered and ignited. The major features are that the normal shock is positioned within the inlet and that the nozzle is choked with supersonic flow behind it.

These results correspond closely to the predicted theoretical values.

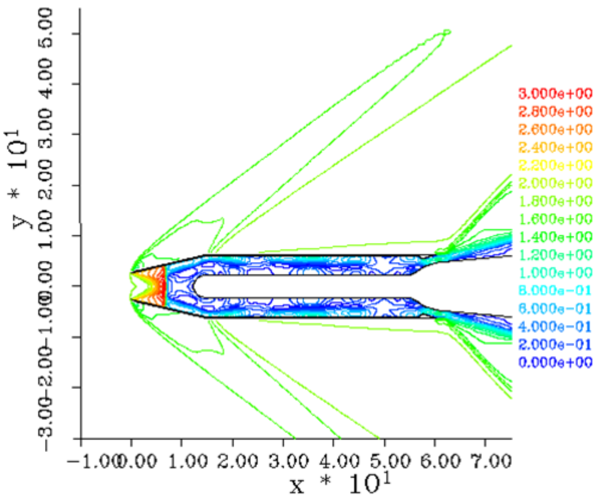

Figure 4: Mach number results for Mach 1.8 non-combusting flight

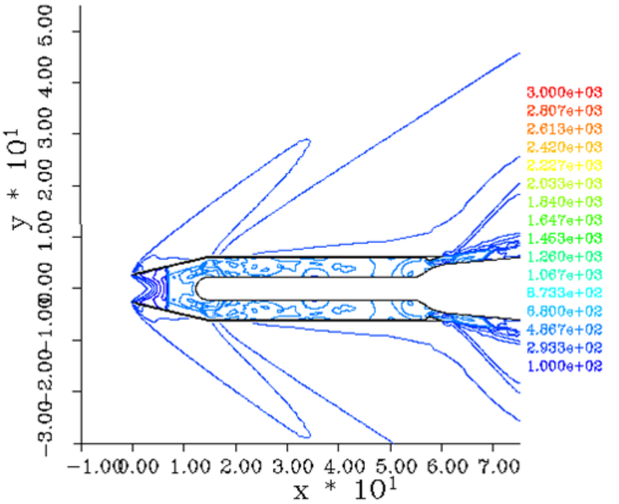

Figure 5: Temperature results for Mach 1.8 non-combusting flight

CFD –Combustion

Using a single step reaction scheme, heat was added to simulate combustion of the fuel/air mix. A reaction zone was specified in the combustion chamber as was the amount of heat to be added from the reaction.

As for the non-combustion simulations, the combustion simulations were run as transient problems however the initial solutions used were the steady non-combustion solutions for the corresponding free stream velocity. In contrast to the transient behaviour of the non-combustion solutions, the transient behaviour of the combustion solutions is likely to be closer to that which would be expected in reality. As heat is added and combustion occurs, the shockwave is pushed out of the inlet and flow is spilled, before the shock moves back inside the inlet and oscillates around the inlet entrance. Within a few milliseconds, the shock comes to rest nearly exactly on the inlet, as desired and predicted by theory.

Figure 6 and Figure 7 show the steady results for the on-design conditions of Mach 1.8 and average fuel delivery rate, which corresponds to a stoichiometric ratio mixture.

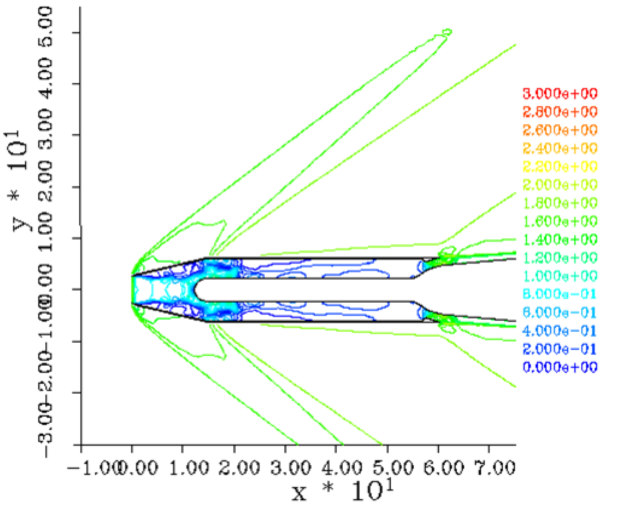

Figure 6: Mach number results for Mach 1.8 flight and combustion with average fuel delivery rate

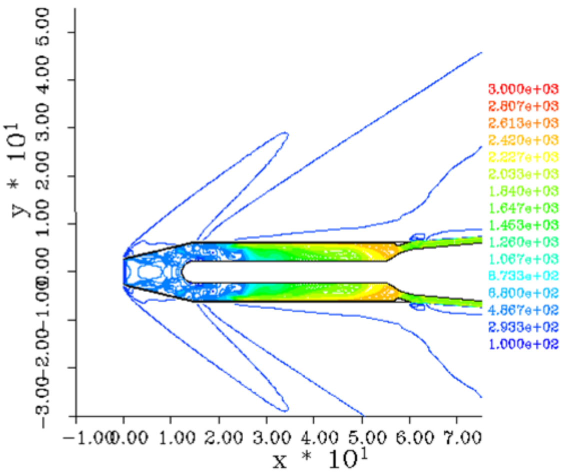

Figure 7: Temperature results for Mach 1.8 flight and combustion with average fuel delivery rate

CFD – FASTRAN

For comparison purposes, individual components were simulated in FASTRAN. The results obtained were consistent with both those obtained with MBCNS and theory.

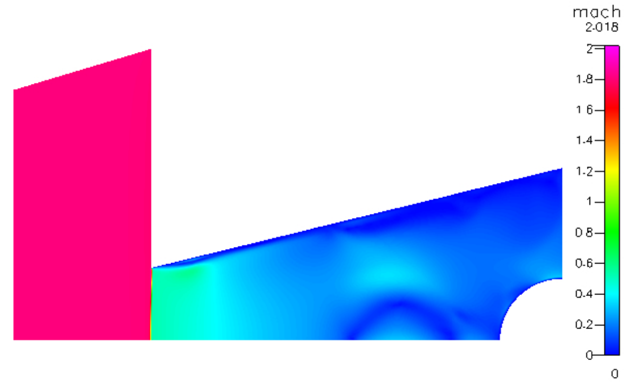

Figure 8: Inlet Mach number results during combustion obtained using ESI Ace

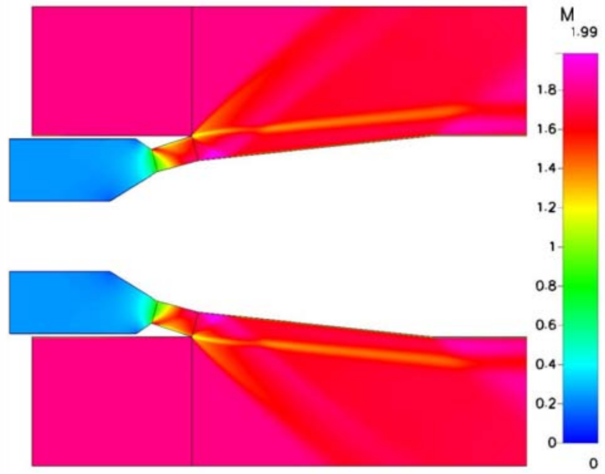

Figure 9: Mach number results for the nozzle at Mach 1.8 flight with combustion, using Fastran

Conclusions

There are numerous fluid mechanics problems which needed to be considered in the design of our ramjet. By investigating these, using theory as well as computational fluid dynamics, we were able to better understand the flow conditions and design our ramjet to operate successfully at these predicted conditions.

Acknowledgments

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