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Transient Heat Analysis of a Carbon Composite Scramjet Combustion Chamber

F.Zander and R.G.Morgan

Centre for Hypersonics
University of Queensland, Queensland, 4072 AUSTRALIA

Abstract

A preliminary 2D transient analysis for a predicted trajectory in a representative scramjet flight path is presented. This model incorporates hypersonic convection and radiation heat transfer at the combustor walls and heat transfer to the fuel which is used as an endothermic heat sink. A heavy hydrocarbon fuel is selected due to the high density and energy release required for combustion, whilst still providing the necessary heat sink for cooling. In this process the fuel can be cracked to smaller carbon chained molecules for improved ignition and combustion. This analysis will be used in parallel with materials development to ensure appropriate composites are available in Australia for flight structures.

The results show that for a postulated Mach 8 scramjet flight at 27km altitude that a combustor structure comprising of 1mm RCC, 1mm graphite foam insulation and a 3mm inconel fuel manifold the maximum temperatures reached are of the order of 1950K in the RCC. This falls within the temperature range allowed for the chosen materials to ensure that structural integrity is maintained. These results justify the further investigation into the use of composite materials and regenerative cooling with the aim of potentially using the analysis for the design of flight vehicles, including the upcoming HiFire series of experiments.

Introduction

Scramjets present a challenging thermo-fluids problem due to the use of hypervelocity ducted flows with no direct cooling path for the internal aerodynamics. Composite materials potentially offer an efficient solution for these design problems due to their high strength to weight characteristics and their high heat resistant properties. Initial scramjet flight paths are likely to be in minutes rather than hours, meaning that equilibrium thermal balance may not be achieved and the operation under transient conditions will be very important. This paper investigates heat flux calculations using a carbon composite scramjet combustor in conjunction with transient regenerative cooling. This technology may offer a very efficient option for future flight model scramjets by dissipating structural heat loads in the fuel.

Previous scramjet flights have relied on the transient thermal storage capacity of the structure to absorb the very high aerodynamic heating loads involved. Typically, this means that after times of the order of five seconds safe working temperatures will be exceeded in the airframe and structural failure results - eg. HyShot, HyperX. This approach is satisfactory for preliminary proof of concept flights to demonstrate supersonic combustion operation, overall vehicle flight stability and airframe-engine integration. However, sustainable cruise cannot be achieved this way. This paper presents a configuration which reaches equilibrium heat balance and has the potential for indefinite sustainable flight.

In the transient mode of operation regime, the designer has many variables which can be adjusted to delay the onset of material failure for the short amount of time required (eg. excessive thickness of components beyond structural requirements to add thermal storage capacity, strategic addition of heat sinks etc.). However, once steady state is reached a very careful matching between equilibrium thermal temperatures, various modes of heat transfer and all material properties is required which applies significant design constraints.

Scramjet Model

The purpose of this investigation is to evaluate the plausibility of using composite materials for a scramjet combustor. Due to the high temperatures expected in the combustor the most likely solution is reinforced carbon-carbon(RCC). RCC is capable of withstanding extremely high temperatures whilst maintaining structural integrity. The two mechanisms for dissipating the heat load are radiation to the atmosphere and regenerative cooling. The external radiation has no further structural requirements as RCC radiates sufficiently so as not to require an extra radiative surface. To enable the regenerative cooling a fuel manifold is required which is conductively attached to the combustor allowing the heat transfer to the fuel. Inconel is used for the manifold as it has a high temperature capacity and will enable the maximum possible heat transfer to the fuel. To regulate the manifold temperature a layer of graphite foam is used between the RCC and the inconel. The thickness of this is determined throughout the analysis and is set such that the maximum inconel temperature is 1200K which represents its structural thermal limit[6].

A structural analysis of the stresses in the combustor resulting from the expected pressures show that a minimal thickness RCC layer is required to maintain integrity. A 1mm layer of RCC is chosen as a practical minimum for manufacturing purposes. The inconel fuel mainfold is taken to be 3mm thick from the insulation to the fuel lines as this is deemed a reasonable thickness to enable the fuel passages to be incorporated. The required thickness of the graphite insulation is then calculated in the Mach 8 analysis to be 1mm. This will vary according to the conditions being analysed.

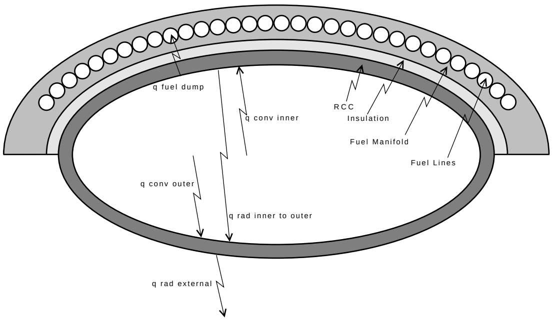

Figure 1: Combustor cross-section

The analysis of the convective heat transfer requires the distance from the leading edge to be known so that the boundary layer characteristics can be calculated. This requires a calculation of the inlet, in this case the scramjet is considered to be mounted on the lower surface of a larger vehicle using the surface of the vehicle for flow compression. As the analysis is 2D the lengths calculated are representative only, however a comparison with shorter realistic lengths show that the effect is minimal on the overall heating rates. The lengths calculated from the leading edge to the combustor entry are 4m for the body side and 0.3m for the external side. The other critical dimension required for the analysis is the cross-sectional area of the combustor which enables the calculation of the mass flow rate of the air and therefore the fuel. This is critical for the calculation of the possible energy removal through the use of an endothermic heat sink. The combustor area for this analysis has been taken as an ellipse with an aspect ratio of 1.8 and a major chord length of 0.1m. The combustor has a nominal length of 1m.

The fuel used for the analysis is octane as a representatvie liquid hydrocarbon fuel with high heat sink capacity and high density enabling a larger amount of energy to be stored. The equivalence ratio used for the combustion is 0.67. The heat sink capacity of the octane is taken from the experimental values found by Huang[1]. This enables the calculation of the heat sink which drives the temperatures reached in the structure of the combustor. Using the fuel as the heat sink has the advantage of heating and 'cracking' the fuel which enables combustion to occur more readily and adds the effects of aerodynamic heating to the thermal cycle. A complete analysis will require the modelling of the multi-phase flow that occurs in the fuel lines to get an accurate measure of the heat transfer.

Analysis

The analysis is conducted for a constant altitude flight of 27km travelling at Mach 8. This corresponds to a postulated scramjet test flight that will occur in the forthcoming HiFire series for which such an analysis is useful. The total time of analysis is long enough such that thermal equilibrium is reached which for the final configuration was 20 seconds.

The transient heat transfer analysis was conducted using an implicit scheme to calculate the changing component temperatures with regards to time. The combustor was modelled as a grid in the x and y directions (down the length of the combustor and through the walls of the combustor) and for each step in the x direction the equilibrium heat transfer was calculated for a small time step. The heat flux at each axial station was modelled independently of all other stations in a quasi 1D approach. This was completed down the length of the combustor to give a full set of data at each point in time. In each time step as the wall temperatures changed the heat transfer changed - this was continued until equilibrium was reached.

Each discreet segment has a net heat transfer in the radial, y, direction. This includes radiation, convection and conduction as determined by the location of the segment. The axial heat conduction is not incorporated as it is orders of magnitude smaller than the radial heat conduction. The heat rise of each segment is calculated using the physical properties of the segment and the net heat transfer to or from the segment. Equations 1 and 2 show the heat balance for a segment on the combustor wall and for a segment inside the combustor wall as shown in figure 2. The equations are formulated such that a positive heat transfer value represents energy into the segment. Equation 2, which only has conduction terms, shows this by the directionality of the temperature difference. The superscripts shown denote the time step and the subscripts denote the radial location of the segment going from A to n from the external surface towards the internal surface. The segment size used for the analysis is 0.1mm resulting in 60 radial segments.

$$\frac{\rho C_p V(T_N^{P+1} - T_N^P)}{\Delta t} = \dot{q}_{cond} + \dot{q}_{conv} + \dot{q}_{rad} \qquad (1)$$

$$\frac{\rho C_p V(T_N^{P+1} - T_N^P)}{\Delta t} = \dot{q}_{cond(N-1)\to N} + \dot{q}_{cond(N+1)\to N} \qquad (2)$$

In equation 2 conduction is calculated using linear interpolation between segments.

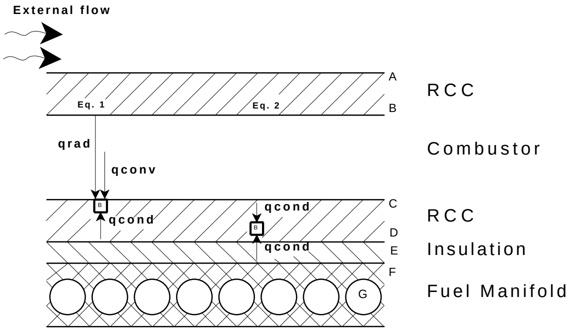

Figure 2: Segment derivation description

Radiation heat transfer is used during the analysis on the outer shell of the combustor and across the internal walls of the combustor. The only material characteristic that effects the radiation heat transfer is the emissivity of the RCC. This is taken to be 0.9 for the purposes of this analysis. The temperature of the external surface of the combustor is very important as this drives the radiative heat transfer to the atmosphere which is an important source of heat dissipation.

The internal convection heat transfer is calculated using Stollery and Colemans relation [2] for flat plate turbulent heat transfer shown in equation 3. This has been shown experimentally by Morgan and Stalker [3] to give a first order estimate of the heat loads in a scramjet combustor. This analysis is based on the boundary layer conditions and assumes that the combustion occurs away from the walls and only influences the heat transfer by changing the pressure in the boundary layer. The pressure down the length of the combustor is assumed to be constant throughout. This is achieved by the use of a diverging combustor which is designed to maintain the pressure at approximately 100kPa.

$$\dot{q}_w = \frac{0.0296}{Pr^{\frac{2}{3}}}\rho^* u_e(H_r - H_w)\left(\frac{\rho^* u_e x}{\mu^*}\right)^{-\frac{1}{5}} \qquad (3)$$

The conduction heat transfer is critical for the analysis as the conduction determines the temperature of the walls and this drives the amount of heat dumped both radiatively and to the fuel. The values of thermal conductivity for the inconel fuel manifold and the graphite insulation are well known material properties however the thermal conductivity of the RCC is very difficult to estimate as the values found in the literature differ by up to three orders of magnitude. The reason for this is that the thermophysical properties of composite materials are very dependent on the manufacturing techniques. Changing the manufacturing process can in fact cause the properties to be changed by a large amount. For the purpose of this analysis the thermal conductivity perpendicular to the fibre path was taken to be 5W/(mK) as found experimentally by Dowding[4]. The thermal conductivity would ideally be very high on the external combustor surface so that the temperature gradient across the structure

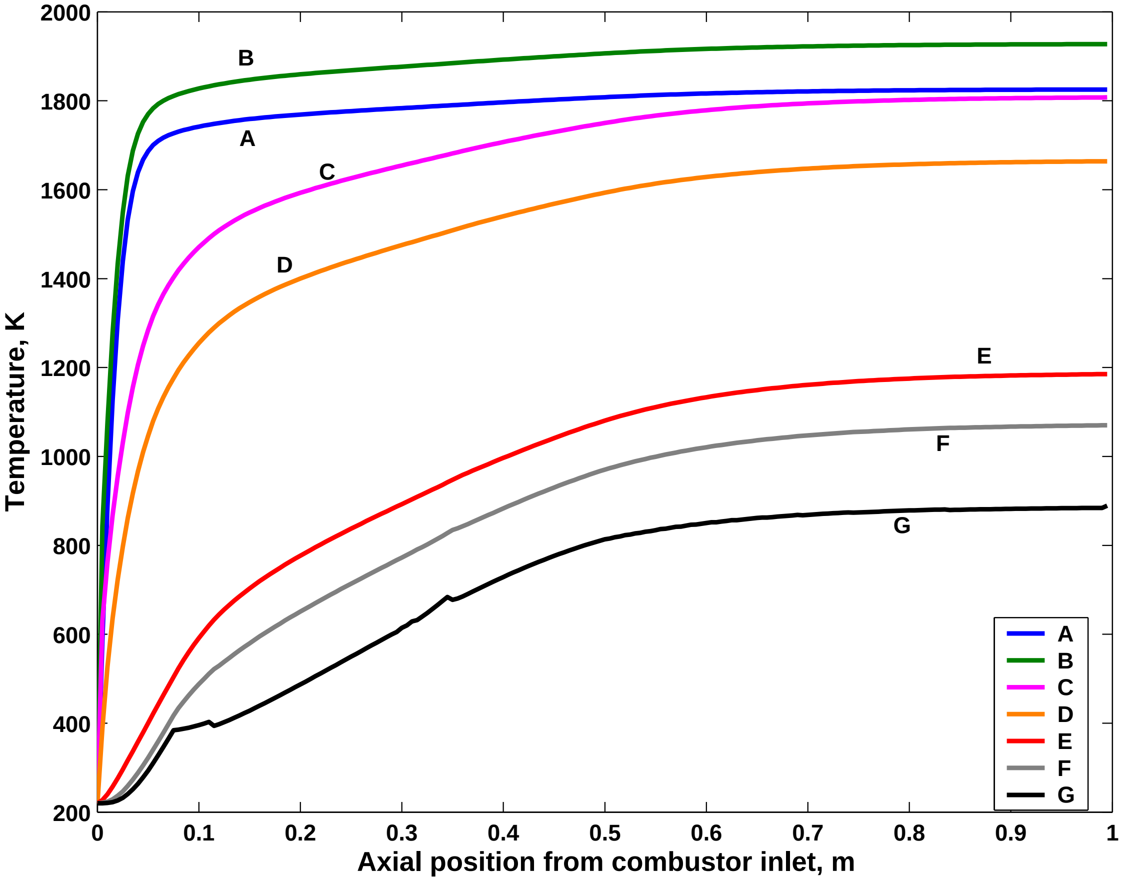

Figure 3: Equilibrium temperature distribution along combustor; see figure 2 for y locations of curves

is minimised allowing the maximum possible external radiation to remove heat. In contrast, on the internal surface a lower thermal conductivity would be preferred as this would minimise the temperature of the fuel manifold, this however can also be regulated by the use of an insulating layer between the combustor and the manifold. From these considerations the RCC must be chosen or developed with properties that enable sustained flight without reaching the thermal limits of the materials.

The heat sink ability of the fuel is a driving factor in the calculation of the temperatures that are likely to be encountered in the combustor walls. The first component of this is the amount of energy that the fuel can absorb and the second is the ability to transfer the heat to the fuel. For the purposes of this analysis the fuel is assumed to travel through 5mm diameter pipes covering 80% of the internal combustor surface. The heat transfer has been calculated using a turbulent pipe flow heat transfer equation [5] and the known temperature difference between the pipe wall and the fuel. The heat absorption capacity of the fuel is highly dependent on the temperature and increases as the fuel progresses through physical absorption (heating up) and chemical absorption (thermal cracking). This process is complicated to model as it involves changes of phase and chemical changes which means the properties of the fuel change very rapidly. To avoid modelling this process the energy absorption is taken from the experimental data found by Huang [1]. The fuel is segmented in the same manner as the structure and from the energy input into an individual segment the heat rise can be calculated and from this the new temperature of the segment is found and used in the next iteration. The fuel is also moved along the combustor to simulate the fuel flow that would actually be occuring. This analysis considers the fuel to be moving from the front of the combustor to the back as this allows for the optimal heat dissipation.

Results

The transient effects of the start up flow are shown not to be in excess of the thermal equilibrium conditions. The entire combustor shows a steady temperature increase with time until the equilibrium is reached. The analysis shows that the thermal transport properties of the materials are sufficient so that the heat load can be dissipated before any components reach critical temperatures. This demonstrates that a combustor of this design would be feasible for a flight model scramjet with a potential flight time in the order of minutes which is of interest for near future launches.

The analysis conducted showed that the required insulation thickness to enable maintainable wall temperatures is approximately 1mm. This results in a maximum wall temperature of 1950K at the front of the combustor on the external combustor wall. Figure 3 shows equilibrium temperature breakdown through the combustor walls for different y locations. This also shows that the maximum temperature that the inconel reaches is less than 1200K which falls within the requirements to maintain structural integrity. The maximum fuel temperature is shown as approximately 900K which is hot enough to ensure that thermal decomposition is occuring. The thermal equilibrium is reached after approximately 15 seconds.

Figure 4 shows the temperature vs. time curves for various points through the thickness at a length 0.5m down the com-

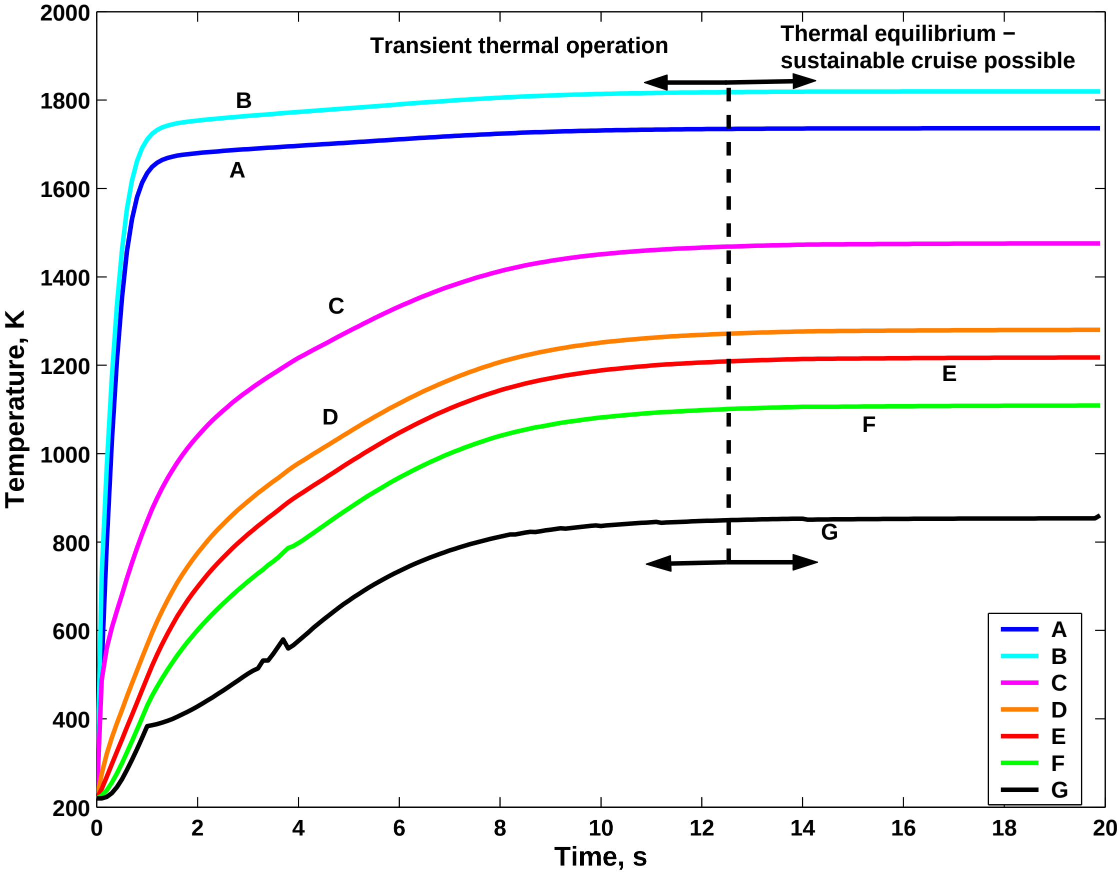

Figure 4: Temperature distribution at x = 0.5m; see figure 2 for y locations of curves

bustor. At this point it can be seen that the thermal equilibrium is reached after approximately 12.5s. The anomalies seen in the fuel curve are due to changing fuel properties during a phase change however the effects of this are negligible to the end result.

The temperatures calculated are within the upper limit of temperature specifications for the materials used and present a structure that could feasibly survive a reasonable length flight test. The length of the flight test possible would depend on the ablation/erosion of the combustor and the acceptable limit of this.

Future Work

A major part of the combustor design is the use of the regenerative cooling offered by the fuel. Thus far in the analysis data has been used from experimental work that has been conducted with a specific configuration [1]. Although this is sufficient for the initial analysis further work is required to determine more accurately the heat transfer and energy absorption in the fuel. These two different mechanisms will have a major impact on the further analysis of the combustor. The heat transfer to the fuel is a complex mechanism that requires extended analysis. The heat transfer will vary dependent on various parameters however the major factors will be the routing of the fuel, i.e. the path the fuel travels along the combustor wall, and the phase of the fuel. As the fuel is heated and cracked it will go through different phases of flow and also change chemical species, this will change the physical properties of the flow and hence affect the heat transfer. This mechanism will require modelling to ensure that the overall analysis is still valid.

The energy absorption of the fuel is also important in regards to the combustion as heavy hydrocarbons will not combust as easily as the lighter hydrocarbons formed due to the thermal cracking. The extent of the thermal cracking required to ensure combustion needs to be defined and this needs to be incorporated into the design.

The other component requiring further development is the manufacturing and testing of the materials intended to be used for the combustor. This refers in particular to the RCC whose properties vary greatly depending on the manufacturing method and quality. An experimental investigation is being undertaken at UQ which will look at different post processing options and determine what thermal and physical properties can be achieved in the manufacture of the RCC. Although the stresses resulting from the pressures in the combustor are minimal an analysis will be required to consider the thermal stresses and gradients resulting in the structure due to the temperature increases seen throughout a test. The longer term objective of this would be to use RCC in flight testing for the HiFire program.

This work also shows potential to apply the same technologies to higher speed vehicles. This will become important as Mach 10 and Mach 12 scramjets will be investigated heavily in the near future. At these speeds modifications to the design will be required to efficiently cope with the heat loads, this may include the use of air gaps between the combustor structure and the fuel manifold.

Conclusion

The analysis conducted in this work has shown that the proposed scramjet combustor design is feasible at Mach 8 under both transient and equilibrium thermal conditions. The combustor configuration with 1mm RCC, 1mm graphite insulation and a 3mm inconel fuel manifold with the use of regenerative cooling and octane fuel never reaches temperatures in excess of the material limits. This justifies the continued analysis and further work, outlined above, as this may represent an engineering design that could be flown in the near future on long duration scramjet flight tests. This work will be extended to include different fuel types and combustor configurations enabling analysis of scramjets currently being considered for flight.

Acknowledgements

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