HEAT TRANSFER MODES IN SUPERSONIC HYDROGEN COMBUSTION

Sara Esparza
NASA URC SPACE
Center at CSULA
Los Angeles, CA, USA

Benjamin Liu
NASA URC SPACE
Center at CSULA
Los Angeles, CA, USA

Cesar Olmedo
NASA URC SPACE
Center at CSULA
Los Angeles, CA, USA

Azizkhan Pathan
NASA URC SPACE
Center at CSULA
Los Angeles, CA, USA

Helen Boussalis, Ph.D.
NASA URC SPACE Center at CSULA
Los Angeles, CA, USA

Darrell Guillaume, Ph.D.
NASA URC SPACE Center at CSULA
Los Angeles, CA, USA

Chivey Wu, Ph.D.
NASA URC SPACE Center at CSULA
Los Angeles, CA, USA

ABSTRACT

A miniature wind tunnel has been built which harnesses the power to hold supersonic flows and supersonic combustion. Experiments have been performed to test the sustainability of hydrogen combustion in supersonic Mach flows. Supersonic combustion allows hypersonic flight viability. Compressed air at different pressure inlets was combined with hydrogen at a constant flow rate for the combustion reaction. Pressure ratios across the flow chamber corresponded to supersonic Mach numbers of about 2.5. The ensuing fuel-air mixture ignited with miniature spark plugs to initiate and sustain combustion at the high Mach flow. Special attention was paid to the pre-mixture of the hydrogen fuel and incoming air because of the relationship between pre-mixture and flame stability. The stability of combustion is especially important in high-speed flight, as seen in ramjet and scramjet design. The combustion reaction within the scramjet engine transmitted heat by means of conduction, convection and radiation, but not much change in temperature was seen, as predicted theoretically, within the engine because of the small scale. However, large temperature gradients were seen throughout the shrouds of the combustion chamber because of conduction. Different materials were used for shrouds to see the various effects of the materials variation as heat sinks for the combustion reaction. Experimental results are verified using laser diagnostics in cold flow, and theoretical analysis is also used in parallel to anchor and check data collected by sensors.

INTRODUCTION

Hypersonic flight vehicles require supersonic combustion. Supersonic combustion must be sustainable throughout flight to avoid severe damages and crashes. The typical shape of an integrated ramjet engine includes an inlet, a combustion section, and an expander. The inlet serves as a compressor, which forces the outside incoming air to the supersonic realm (Mach 1.0 or higher). Ramjets are airbreathing meaning the surrounding air enters the vehicle and is used as an oxidant. The combustion is sustained within the combustion section. For hypersonic vehicles, the combustion must be maintained at supersonic speeds, or speeds at least double that of the speed of sound. The expander is a diffuser that allows the supersonic exhaust flow to speed up, bringing it to hypersonic speed, which is at least five times the speed of sound (Mach 5.0).

The advantage of the completion of the development of supersonic combustion is that it makes low hypersonic flight possible. Reentry vehicles travel at high hypersonic speeds and hypersonic flight vehicles are very difficult to control. Hypersonic flight vehicles travel too quickly to turn and maneuver easily. Vehicles that operate at low hypersonic speeds are easier to control and the realm of low hypersonic flight can be achieved through supersonic combustion. Since low hypersonic flight can be more easily managed and controlled, a significant database should be developed to include all aspects of supersonic combustion and hypersonic flight.

NOMENCLATURE

A	Area, cross-sectional area, surface area
c_p	Specific heat at constant pressure
c_v	Specific heat at constant volume
D	Diameter
E	Energy
h	Convection heat transfer coefficient
L, l	Length
q	Heat
q'	Heat per unit length
q"	Heat flux
T	Temperature
t	Time, thickness
V	Volume
w	Width
π	Pi
ρ	Density
dT/d_	Temperature gradient in (_) direction

Subscripts & Superscripts	
s	Surface
x	Taken in the x-direction – Cartesian coordinate
∞	Free-stream

Experiments have been performed to test the sustainability of hydrogen combustion at high speeds. Current research models only the combustion section of the scramjet, but future work is in progress to simulate the compressive inlet and expansive outlet sections of a scramjet (supersonic combustion ramjet). Inlet and outlet ramjet designs require pinpoint accuracy to harness the developing shockwaves.

The stability of combustion is especially important in high speed flight, as seen in ramjet and scramjet design. Combustion within ramjets occurs under very harsh and unstable conditions due to the high pressure and shock waves. It is therefore important to study different parameters which might increase or decrease the possibility of sustainable combustion, such as the equivalence ratio, pre-mixture ratio, fuel inlet rifling, cavity design as a flame holder and volumetric flow rates of the combustion reagents.

Fuel, heat and air are needed along with an ignition source and a flame holder for stable combustion to occur. Hydrogen is used as the fuel for the high speed combustion. Hydrogen has a very low activation complex making it very easy to combust. Hydrogen fuel also has a high internal energy allowing it to maintain a high energy flame which is relatively difficult to extinguish. It is an ideal fuel for supersonic combustion.

The hydrogen-air reaction Equation is balanced as follows:

$$2H_2 + (3.76N_2 + O_2) \rightarrow 2H_2O + 3.76N_2$$

The right side of the Equation above shows the products of hydrogen combustion. It can be seen that nitrogen and water are the only direct bi-products of hydrogen combustion. Thus hydrogen serves as a clean fuel unlike heavy hydrocarbons which directly emit greenhouse gases.

When the diatomic nitrogen is released in hydrogen combustion at very high temperatures, it might create nitrous oxides causing one harmful bi-product but it is not directly emitted from the hydrogen combustion. This is a caveat for researchers and engineers employing hypersonic flight vehicles. This product must be taken into account when testing with air rather than oxygen as in this experiment.

A Dewalt compressor was used to compress air the air compressed range was from 120 to 180 psi. This air was introduced at the inlet at different flow rates and pressures to combine with hydrogen at a constant flow rate and was excited to initiate combustion. The combustion maintained was rich in nature, meaning that more fuel was added than the stoichiometric ratio seen in Equation (1). The combustion was rich to ensure adequate fuel in combustion and to avoid burn out even though lean flames would have been safer.

Combustion includes the ignition of fuel and air, mixing of the fuel and air before and after ignition and flame stabilization practiced to sustain combustion for a while after the flame has been established. As mentioned above, heat is added to air-fuel mixtures to incite and sustain combustion. These three parameters, air, fuel and heat, may be added separately or in conjunction. For instance, the fuel and air may be added together before combustion occurs. This is called premixture. Flame stability depends highly on the amount of premixture. Mixing can occur by molecular diffusion when two substances of different atomic mass interact. The lighter substance diffuses into the heavier substance at a rate inversely proportional to the size of their atomic makeup. As previously mentioned, pre-mixed flames are more stable, can be maintained at higher inlet air speeds and produce less soot and emissions. Pre-mixture can effectively increase combustion stability. Pre-mixture is employed with varying fuel-air amounts to study the effect on the stability of the combustion. Pre-mixture greatly increases the maintainable speed of combustion. The limitation of pre-heating is combustion chamber material and its ability to keep its mechanical integrity at elevated temperature. Pre-mixture also increases the chances of dangerous and unanticipated combustion.

Mixing can also be increased by using a cavity. An open cavity is a step in the combustion chamber which causes a difference in flow speed and a shear boundary layer. The correct cavity size was determined by testing different cavities sizes with a Schlieren system.

Currently we are using a cavity with a 0.03” depth and length of 2.0”. As mentioned above, the cavity also allows for the air and fuel to recirculate inside the flow chamber. There are two flow regimes of recirculation for a cavity as stated by Ben Yakar and Hanson [1]. The cavity can be either open or closed. The regime is based on the length to depth ratio of the cavity. Currently the cavity is open since its length to depth ratio is large and it empties out of the combustion chamber. Unlike the references where the cavities are rectangular our cavity is ovoid in design. In an open cavity, the air and fuel recirculation occurs right after the rearward facing step in our cavity.

The recirculation can be modeled after pressure fluctuations at a Mach number range from 1.5 to 2.5. At speeds higher than Mach 5 cavities do not produce pressure fluctuations due to the high Mach number.

Frictional drag also causes pressure fluctuations within the cavity. Although this may appear as an advantage to increase recirculation in the cavity, too much drag can reduce flow velocity producing subsonic (rather than supersonic) flow. This is another reason why verification of shock wave via Schlieren system is critical to combustor design. A stable cavity with recirculation can be used as an efficient flame holder. A stable cavity recirculation will reduce turbulent mixing. A balance has to be developed to balance a stable recirculation cavity with turbulent mixing.

The hydrogen fuel inlets will be rifled to increase mixing in the circular combustion chamber. Rifled fuel inlets will produce vortices inside the combustion chamber to enhance mixing throughout the length of the chamber producing a swirl of air and fuel near the chamber walls. The rifling is achieved by machining hydrogen fuel lines into the combustion chamber separated by 120 degrees. The fuel lines are also angled into the combustion chamber wall so that hydrogen gas is introduced at that same angle.

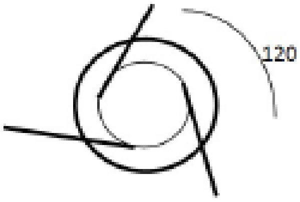

Figure 1 – Rifling Fuel Inlets Increases Mixing

Ignition

Another advantage of premixing is that it can serve as a pre heater. The advantage of a pre heater is stable combustion and it also heats the combustion chamber to operation temperature. This increase in temperature serves as a source of heat to ignite the hydrogen without an ignition source. A disadvantage to an ignition system is that it impedes the supersonic flow through the chamber causing bow shocks and reducing flow.

In order to ensure ignition of the fuel-air mixture, miniature spark plugs powered by small Tesla coils. Spark plugs are more reliable than compression ignition and are more easily controlled and timed. The frequency of ignition is very high. The sparks within the combustion chamber are almost continuous. Three Tesla coils power one spark plug each. The Tesla coils are evenly spaced radially around the chamber. The spark plugs are slightly receded to avoid interaction with the chamber flow.

Dynamic Characteristics

Many changes in temperature, pressure, velocity and other parameters are seen due to the very nature of compressible flow and combustion. Therefore the operand del must be used.

$$\nabla = \left(\frac{\partial}{\partial x}\hat{i} + \frac{\partial}{\partial y}\hat{j} + \frac{\partial}{\partial z}\hat{k} \right)$$

The combustion reaction is modeled as a point mass which radiates heat outwards. The heat is dispersed by various means, because all three modes of heat transfer are present in high speed combustion flows.

$$q'' = -k(\nabla T)$$

Heat generated within the combustion chamber dissipates throughout the cylindrical engine walls by means of conduction which follows Fourier's law.

$$q''_x = -k\frac{dT}{dx}$$

Convection heat transfer can be seen between air and fuel flows which enter the flow chamber through their respective injectors.

Before the combustion section, the chamber walls are cooled by the air flow. At the exit of the converging diverging nozzle, the air reaches Mach 2.5. This air is colder than room temperature due to the high Mach number which is inversely proportional to temperature.

$$q'' = h(T_s - T_\infty)$$

$$h = 0.023\,\mathrm{Re}_D^{4/5}\,\mathrm{Pr}^{0.4}\,\frac{k_f}{L}$$

Radiation cannot be ignored when combustion is present. Surface to surface radiation and gas radiation must be considered.

$$q'' = \sigma\varepsilon\left(T_s^{4} - T_{surr}^{4}\right)$$

Hydrogen gas and water vapor interactions were taken into account when calculating the total emissivity and absorptivity of the gas flow within the combustion chamber shroud.

Some necessary heat transfer parameters are summarized in the following table:

Material	Thermal Conductivity, k	Emissivity, ε
Aluminum	237.	0.04
Stainless Steel 304	14.9	0.22
Laboratory Air	0.1	0.01

The heat transfer throughout the inside of the shroud is very small due to the miniature size of the experimental apparatus. The hydrogen combustion provides a small given input heat flux as well. Even though conduction, convection, and radiation are taken into consideration to dissipate the heat, the temperature of the flame drops only 6% from 1588.7 K to1493 K.

The heat dissipation throughout the aluminum and stainless steel shrouds are significant, since there is a great amount of material which serves as a heat sink.

Experimental Setup

Sustainable supersonic combustion requires a long chamber as shown by compressible mixing thickness equations. When calculating the compressible flow mixing thickness it is evident that you will need to design a long combustion chamber to achieve a supersonic mixing to a level that will allow combustion and maintain it.

Cavities produce a pressure drop and a change in velocity between the air and fuel flow velocities inside the chamber. It produces a similar effect as the splitter plate. It also allows the air to recirculate inside the cavity. The recirculation depends on the size of the cavity.

The cavity size is determined by the combustion chamber diameter. If the cavity is too large relative to the size of the chamber, the cavity will produce a significant pressure drop and a bow shock will then cause the flow to be subsonic, eliminating supersonic flow. We determine this by testing different cavities sizes with a Schlieren system.

Physical tests are necessary to examine the flow and combustion described by the above theory. Many tests and experiments have been run to induce and sustain supersonic combustion. Testing includes examination and operation of the individual and total components of the supersonic combustion flow bench.

A flow chamber brings air to Mach 2.5 and produces supersonic combustion. The air is brought up to speed with a converging diverging nozzle and outlet into the main flow combustion chamber.

At first, the supersonic converging diverging nozzle is tested alone with the test pressure as an initial condition to create high speed flow. A compressor was used to bring shop air to 120 - 180 psi and inlet to the nozzle. The nozzle was then outfitted with a pressure reader that measured the dynamic pressure at the exit of the nozzle. The pressure ratio across the nozzle was then found and checked with compressible flow tables in Anderson's text [2].

Compressed air was supplied at varying inlet pressures ranging from 120.0 – 180.0 psig. The inlet air entered the converging-diverging, or De Laval, nozzle. The converging-diverging nozzle produces 6.83 psia as an outlet pressure, which at room temperature corresponds to Mach 2.57.

The main flow combustion chamber contains a cavity located on one side of the central axis. The cavity is created by an offset hold increasing the cross-sectional flow area by 12%. The combustion chamber has three spark plugs radially located 120 degrees apart. The spark plugs are nested, and do not obstruct the flow, but provide a strong, continuous spark to ignite the fuel-air mixture. The three spark plugs are powered by Tesla coils which act as transformers which keep the spark continuous, so spark timing can be overlooked.

Hydrogen (H2) is a colorless, odorless, compressed gas. Hydrogen flames are invisible. Thermocouples are placed at various axial and radial locations to detect temperature and combustion which cannot be detected with the human eye. Below is a graph of the temperature during testing showing high temperatures and combustion of the hydrogen flame.

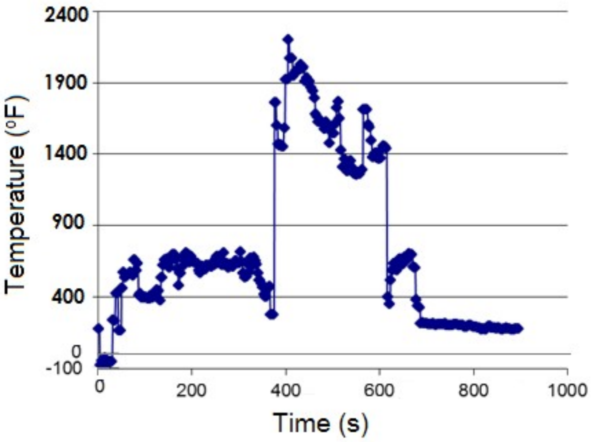

Figure 2 – Startup, Combustion Time and Cool Down Temperature Data from Thermocouple 3

The initial valley represents start up where the air was brought up to speed. The central peaks represent initial combustion and stabilization. The following valley represents cool down and flame extinguishment.

When the flame interacts with its surrounding, some light emissions can be seen as in the figure below.

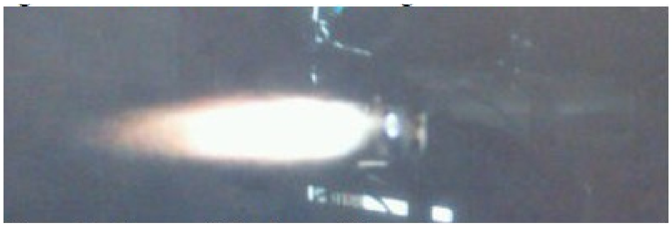

Figure 3 – Supersonic Hydrogen Flame Capture

The Mach number is established using a Schlieren optical system. Cold flow analysis was performed by establishing the same inlet air conditions without combustion, flame, or fuel. The compressible flow and resulting shockwaves were then examined and viewed using a red diode laser using a typical Schlieren setup. Schlieren imaging confirmed supersonic flow. The same parameters used to produce combustion also produced supersonic flow during cold flow analysis. It follows that combustion was produced and maintained in a supersonic flow field.

Future Work

Computational fluid dynamics and other finite element analyses will be performed to anchor experimental and theoretical results with alternate solutions. Future work also includes incorporating all above experimental work, theoretical analyses, and designs into a viable small scale vehicle.

Conclusion

Combustion was incited and sustained at high mach flow speeds. The combustion was maintained using a cavity, specific fuel-air mixture ratios and continuous ignition. The combustion was verified using thermocouples. The high flow speed was verified using laser diagnostics. All three aspects combined prove the sustainability of supersonic combustion which will help propel future high speed flight vehicles.

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