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Assessment of Solid Hydrogen Slurry Fueling for an Airbreathing Supersonic Combustor

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Solid hydrogen particle slurry fueling of a scramjet is investigated through modeling and experiments. Advantages of this concept include supersonic flow penetration of a slurry jet, the potential of cryostabilized fuel additives, and the low losses associated with wall injection. Experimental research has shown that it is practical to pump and inject a 4 K solid H_2/liquid He slurry with a very low helium fraction; the added helium does not decrease combustion efficiency. The critical issue is the solid hydrogen ablation rate; the complex physics of the ablation processes are described noting the importance of liquid droplet shedding. Modeling of a solid hydrogen particle ablating in a Mach 3 flow is described, together with particle lifetime predictions. High-speed single hydrogen pellet injection into an inert gas was performed experimentally to measure its ablation rate. Success of the concept is supported but not conclusively demonstrated. The current state of this patented concept is described.

Nomenclature

A = area
C_D = coefficient of drag
c_p = specific heat at constant pressure
c_V = specific heat at constant pressure
D = diffusion coefficient
d = diameter
e = freestream
l = liquid
k = thermal conductivity
l = length
M = Mach number
$\dot{m}$ = mass flow rate
P = pressure
p = pellet
Q = heat
Q_v = heat of condensation
$\dot{Q}$ = heating rate, W
q = kinetic energy ratio
Re_d = Reynolds number base on diameter
r = radius
s = solid
T = temperature
t = time
U = velocity in the direction of the particle motion
V = volume
V = velocity transverse to the direction of the particle motion
v = velocity
α = thermal conductivity
γ = ratio of specific heats, c_P/c_V
δ = boundary layer thickness
ρ = density

Introduction

THIS paper presents the current status and efforts to assess the feasibility of the patented[1] concept of fueling a scramjet by wall injecting a solid hydrogen (H_2)/liquid helium (He) particle slurry.[2] The primary advantages of the technique would be 1) the elimination of protruding injector losses, 2) the ability of the particle slurry jet to penetrate fully across a supersonic combustor, 3) the capability of adding cryostabilized propellant additives to the solid H_2 to either increase the energy release of the fuel or catalyze the combustion, and 4) a higher fuel density. It may also be possible to inject the solid at high velocity and use its kinetic energy to augment thrust. The primary disadvantage of the technique is that the slurry fuel cannot be used to absorb skin-friction heating. The fueling process itself has already been demonstrated; the slurry can be handled and pumped as a liquid by standard components.

The critical feasibility issue is whether the slurry fuel can mix and combust fast enough. The key physical process that implies extremely fast solid H_2 ablation and mixing is that after the solid is melted, the liquid surface layer is shed in the form of tiny droplets, rather than evaporating at the particle surface. (Liquid H_2 has extremely low viscosity.) The particles are able to penetrate the flow while the droplet shedding disperses the droplets throughout the gas along the particle's path so that the H_2 is rapidly mixed on a molecular scale for combustion. Preliminary experiments to determine whether solid H_2 particle ablation rates are fast enough have so far been inconclusive, and the complexity of the physical processes involved in mixing and combustion have, to date, prevented modeling from implying feasibility and motivating further experimental work.

Engineering Description and Assessment

The engineering issues of solid H_2 slurry fueling include the storage, transport, injection, dispersion/mixing, and combustion of the fuel. Ignition is a separate issue, which will not be considered here. Of these issues, fuel dispersion and mixing is the critical enabler of the concept that will be discussed in detail.

Slurry Transport

The high solid H_2 transport rates required for scramjet propulsion can be readily achieved by pumping a liquid–solid slush. As a two-phase mixture, the solid suspension acts as a fluid that does not have a large viscosity. Laboratory studies[3] of high-speed centrifugal pumping of a H_2 slush (coexisting solid and liquid H_2) showed that the slush pumping characteristics were the same as for the liquid for all pump characteristics for a solid fraction from 0.19 to 0.55. Extensive H_2 slush work has also been done for the National Aerospace Plane.[4] The motivation for this research was the higher density for H_2 storage as a solid and a major reduction in evaporation loss.

The weakness of the pure H_2 slurry approach is that the particle size will probably not be stable; almost certainly, a particle size range

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that includes small particles will lose the smallest particles after a fairly short period as a result of recrystallization in the mixture. Another weakness of this approach is that cryostabilized additives (CSAs) could not be added to the solid. The CSA mixtures are not stable at the high temperature of a coexisting liquid/solid slurry because of constant recrystallization and high diffusion rates in the relatively high temperature solid.

A solid H_2/liquid He slush provides a more attractive fluid. The surface tension of liquid H_2 is a factor of 10 less than that of familiar room temperature liquids, and the surface tension of liquid helium is another factor of 10 less than that of H_2. This means that the liquid helium will surround all of the H_2 particles, even if they are nominally in close contact. Because the solubility of H_2 in He is also low, the recrystallization rate of the H_2 particles should be low, and their size should be stable, even for very small particles. The small amount of He needed to form a stable slurry does not a significantly reduce rocket thrust.[5] Further laboratory work on these slurries at NASA John H. Glenn Research Center[6] has confirmed slurry transport properties.

Fuel Injection/Dispersion/Mixing: Slurry Jets

For scramjet combustor design, the characteristics of slurry jet fueling (injection angle/direction, number of jets, jet density, diameter, and velocity) are defined to optimize mixing in the broadest sense. The breakup of a high-speed particle jet in a supersonic crossflow is a highly complex process, not easily amenable to modeling or small-scale experimental testing. Large (greater than 10 μm) particle jet injection into supersonic flows has never been studied because it has been assumed that there was no way to combust fully such large particles rapidly. Micrometer-sized particles are appropriate to achieve complete combustion in a typical rocket combustion chamber.

The process of the breakup of a slurry jet (Fig. 1) parallels that of a liquid jet; after emerging from the injector, the jet becomes unstable, axial waves form on the jet column, which are amplified, and the waves cause the column to fracture, and the jet disintegrates. It has been demonstrated that a liquid jet must have an injection momentum greater than a certain minimum to penetrate the supersonic stream. For penetration of the stream the q of the injected stream must be greater than 6, where q is defined as $q = (\rho_j v_j^2/\rho_e v_e^2)$; the subscript j refers to the jet, and the subscript e refers to freestream values.[7] During the breakup process, liquid is torn off the front and sides of the jet forming relatively small droplets, while larger

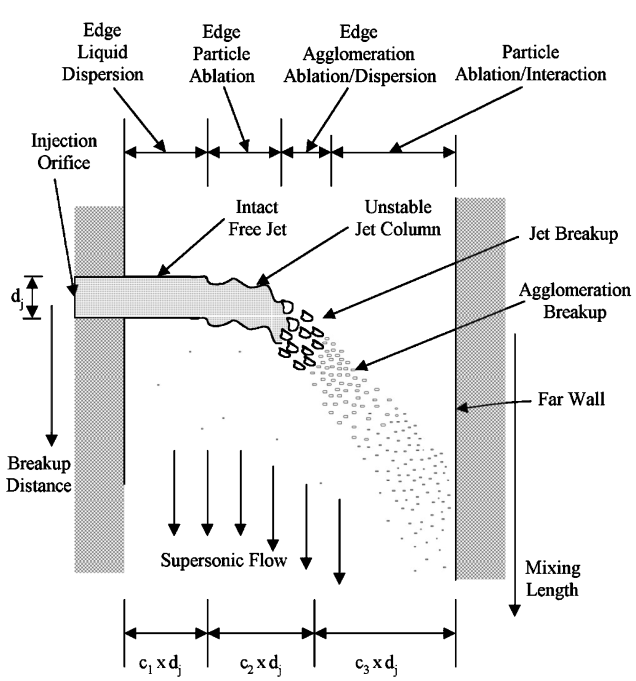

Fig. 1 Schematic of injection processes of a slurry jet into a supersonic flow.

droplets form from the breakup of the jet center. There are three basic zones in jet breakup: the cohesive jet zone, the spray formation zone, and the atomization zone. In the spray formation and atomization zones the droplet size distribution is disturbed by large-scale overall fluctuations in the jet, passages of waves or shed vortices, or the passage of large droplets created by the fracture of the jet. The spray is finally atomized to the extent that the aerodynamic forces become balanced with the surface tension forces as defined by the Weber number and the Reynolds number. The fluid breaks into small droplets and undergoes large accelerations as drag forces overwhelm inertia forces.

In the case of solid H_2 particle injection, the particle size would be on the order of 1 mm and the particle loading would be very high, almost certainly greater than 80%, in the form of a solid H_2/liquid He slurry. With such a high particle loading, it is likely that the q requirements for jet penetration and stability will be lessened significantly because the particle diameter is larger than the wavelength of the jet surface instabilities (about $\frac{1}{3}$ mm). The injection of a liquid jet with a 30% loading of 3–5 μm sand particles has been investigated, and significant penetration of the particles beyond the liquid in the jet was found.[8] There have also been indications that the particles stabilize the jet column. One peculiarity of the H_2 slurry jet is its low specific gravity; the density of solid H_2 is only 0.09 g/cm^3, or 10% of water. Previous experiments used particles with a specific gravity of 3 or higher.

After entering the supersonic stream, the particle slurry jet column quickly (but much more slowly than a liquid jet) develops wave instabilities on its surface that lead to breakup of the jet.[9] The jet breaks into agglomerations of particles of varying size, which continually decrease in size, ending in a cloud of individual particles that then ablate. The liquid and gas ablated from the particles is mixed and combusted as an end to the ablation process.

The problem of combustion at the jet itself, and its effects, has not been addressed. Figure 1 shows how the fuel jet would penetrate the entire duct. It is expected that a wall-injected slurry jet can fully penetrate a typical supersonic combustor, whereas this is not possible with a liquid jet.

For the development of the specific jet shown in Fig. 1, most of the mixing would take place at the far end of the jet. The important timescale for ablation is not the mixing or flow time of the supersonic flow, but the crossflow time of a typical particle, which is usually a longer timescale. A typical scramjet combustor usually has a 10/1 aspect ratio. The time needed to cross a 1.0-m-wide combustor is on the order of 10 ms for perpendicular injection at 100 m/s, or 40 ms for 15-deg injection upstream. Thus, particle ablation need not be extremely fast and can be controlled by changing particle size if the particles are large enough not to be swept downstream by aerodynamic drag. The moderate ablation time and the controllability of solid H_2 slurry fueling increases the probability that this technique will be a feasible technique for real scramjet propulsion.

Based on the density of solid H_2, a flow velocity of 170 m/s would be required for a solid H_2 jet to reach a q value of 6 to penetrate fully a Mach 3 flow at 10,000-m altitude. For a 1-mm-diam H_2 particle in a 1-km/s, 1-atm airflow, $Re_d = 1 \times 10^5$ and $C_D = 0.4$. This implies a force of 0.5 N on the particle for a 0.6-MPa dynamic pressure and implies an acceleration of 4×10^6 m/s^2. For this magnitude of acceleration, the particle will reach 1000-m/s velocity in about 1 ms because the drag on the particle is determined by the velocity difference between the particle and the flow. The 10-m-long combustor transit time of the flow is about 10 ms. The time to accelerate the 1-mm particle to flow speed is small compared with this, so that 10 ms would be the residence time of any H_2 particle smaller than about 1 mm. A 10-ms residence time for a 100-m/s injection cross velocity would imply that the particles would penetrate the full 1 m width of the combustor.

Injecting a jet of solid particles would increase the penetration significantly beyond this because the jet column itself would penetrate 10–20 cm, 5–10 diameters for a 2-cm-diam jet, and during the jet breakup process, the agglomeration size would be much larger than the 1-mm particles. The slowed flow within the dispersing jet would also decrease particle movement downstream. The critical difference between injection of liquid and solid is that liquid injection leads quickly to droplet atomization and liquid scales that are so small that they quickly lose transverse velocity in the flow; this is not true for solid particles. The drag deceleration of a 1-mm particle with a 100-m/s relative gas velocity is a factor of 100 less than that already given, which leads to a deceleration time also on the order of 10 ms. Smaller particles would decelerate more rapidly and, thus, not penetrate the full 1-m combustor in the required 10 ms. A 10-ms ablation time is, thus, a good estimate of the maximum allowable ablation time of a 1-mm-diam solid H_2 particle because it must ablate, and the ablation products mix before the particle traverses the combustor width.

A basic feasibility question is whether the H_2 pellet maintains its integrity when it is injected or cannot penetrate the flow. At $M = 3$ in the combustor, the pressure on the front of the pellet is about 1 MPa. The compressive strength of solid H_2 is probably 10 times its tensile strength, or about 3–5 MPa at 4 K (in a He slurry); thus, it is expected that the strength of solid H_2 is adequate to support the relative pressure stress at the interface. No distortion of the H_2 pellets has been observed in the pellet injection experiments, supporting these calculations. Furthermore, the solid will be strengthened by mixing with other materials such as solid oxygen (stable) mixture or a catalyst that would be used to reduce recombination in the combustion products and increase combustion efficiency.

Modeling

Physics of Hydrogen Ablation

The analysis of solid H_2 particle ablation in a combustion gas environment is extremely complex. There are large simultaneous density, temperature, species, and momentum gradients near the particle, and these gradients not only lead to very complicated transport modeling, but they also result in large variations in what are normally considered to be constant parameters of the problem. One goal of the effort has been to determine the primary rate limiting processes by analyzing engineering approximations to the problem. The constraints and the driving forces of the problem have been largely defined, and a wide variety of simplifying assumptions have been investigated to attempt to make a first-order estimation of the lifetime of the particle. The problem is so complex that experimental testing must complement even a major program of analysis.

Hydrogen particle ablation is a problem in fluid dynamics where there is simultaneous mass, momentum, and energy transport of two species occurring in the presence of phase changes of both species. The gas and liquid flows near the particle are described primarily as boundary-layer flows, but gas is continually evolved from the particle. Boundary conditions include 1) a high-temperature shock-heated freestream flow for relative particle velocities greater than the local speed of sound and 2) a 4 K solid particle. There is probably an internal boundary condition in that the combustion gas condenses at some position in the cold H_2 gas layer and provides a sink term for the external flow.

The overall description of the problem addressed in this modeling is illustrated in Fig. 2. Computational fluid dynamics modeling was unavailable for this program. A particle shape of a cylinder with domed ends was chosen to try to compare modeling results with experimental data for solid H_2 pellet injection. The solid H_2 particle moves through a high-temperature gas that approximates N_2 in composition (for combustion in air). For particles injected into a supersonic flow, there will be a shock wave in front of the particle. The high temperature and pressure zone just behind the shock will be a dominating effect, compressing the gas in front of the particle and increasing heat transfer locally. Because H_2 is transparent at both visible and infrared wavelength, radiant heat transfer is negligible.

The gas layer partially shields the particle from the mass, momentum, and energy diffusing from the combustion gas. A stable equilibrium is, thus, created between the heat flux to the liquid surface and the thickness of the shielding gas layer. If the layer thickens, the heat input decreases, less gas is evolved, and the layer thins, increasing the heat input back to its equilibrium level. The H_2 gas wake partially shields the sides and back of the particle from condensation and heat transfer, so that ablation takes place primarily from the front and sides of the particle. Behind the particle is a wake that consists of both H_2 liquid droplets and H_2 gas. The particles also tumble as they encounter asymmetric forces, further complicating the description.

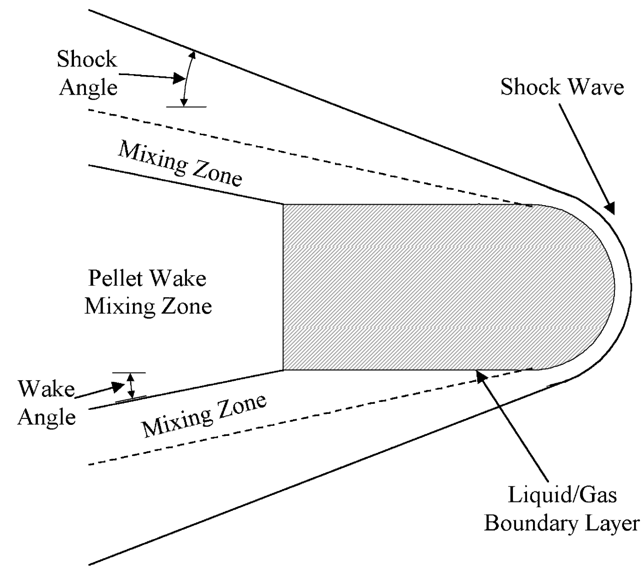

Fig. 2 Schematic of solid H_2 supersonic ablation geometry.

The particle loses mass through vaporization of liquid at its surface and entrainment of liquid droplets shed from the surface into the high-velocity gas that flows around the particle. Determining the heat input to the particle will not determine the ablation rate unless liquid entrainment is unimportant. Liquid entrainment dramatically reduces the heat input necessary for particle ablation because the heat of vaporization is so much larger than the heat of fusion. The particle velocity will be a dominant effect, even without considering supersonic injection. The speed of the particle determines the large-scale thickness of the gas layer, as well as the shear forces on the particle surface that result in liquid entrainment. Particle lifetime decreases with an increase in particle velocity as a result of higher heating rates and smaller diffusion scales of the thinner boundary layers.

The thermal and species (scalar) diffusion problem is fundamentally different from the momentum (vector) diffusion problem. Scalar diffusion takes place where there is no (at the stagnation point) or little (near the stagnation point) momentum transfer: The momentum diffusion occurs normal to the surface but is driven by a velocity difference parallel to the surface that is zero at the stagnation point. The particle ablation velocity boundary-layer problem is different from the problem of boundary-layer growth on a sphere, both because of H_2 blowing and the large pressure gradient associated with the leading shock. Another key difference is that, although the mass, momentum, and heat diffusivities are approximately equal, the species and heat boundary layers are distorted at a specific temperature, where the freestream gas condenses and releases heat, changing the growth rate of both scalar layers. No previous analysis has dealt with this coupling, necessary for solid H_2 ablation.

Simple models and analog experiments are not appropriate because the primary physical mechanism controlling ablation, liquid shedding, dominates the process only for solid hydrogen ablation.

Not only is the problem complex as a simultaneous diffusion problem, but it is complex spatially. All of the important diffusion effects occur at the leading corners of the particle where the boundary layers are the thinnest. For this reason, if the particle initially had the shape of a cylinder (as in the pellet ablation experiments), it will quickly ablate to the more conventional shape of a bullet.

A schematic of the temperature and velocity variation from the pellet surface to the freestream gas is shown in Fig. 3. The plots are not to scale; the liquid layer is much thinner than the gas layer, and T_0 is 100 times the solid temperature. For the case of H_2 ablation,

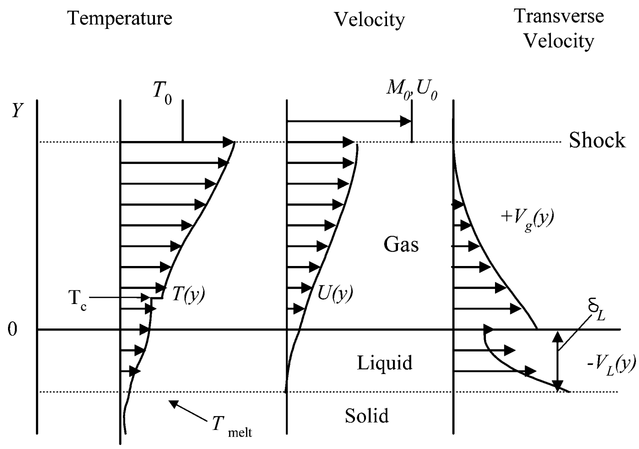

Fig. 3 Representative distributions of temperature, velocity, and transverse velocity for ablation with blowing.

T_0 is 800 K and T_m is 14 K; the temperature continually decreases from its freestream value. Steep temperature gradients that are near the pellet surface result from much lower diffusivities. There is an inflection point near the surface as a result of condensation heat release.

The case of the injection of a single pellet at high speed into quiescent N_2 gas is fundamentally different from the case of scramjet fueling. The pellet ablates with a single normal shock system in front of it, whereas an injected jet of particles undergoes some complex breakup process in multiple shocks into supersonic crossflow. The single-pellet experiment and analysis, however, has been used to provide a foundation for understanding and predicting behavior in the particle jet.

Particle Lifetime Estimates

A simple minimum timescale for pellet dissipation is estimated as follows by a thermal (not a dynamic) analysis of the heat transfer needed to vaporize the pellet.

Solid H_2 is unique in that it exists at a temperature that will condense any other gas except He. An H_2 pellet moving through air can condense the air and release the heat of vaporization at or near the surface of the pellet. For this reason, an approximate minimum lifetime of a pellet traveling at $M = 3$ through l-atm air can be calculated if it is assumed that all of the air in the pellet's path is condensed to a liquid and the heat released is used to melt the solid H_2 that then is shed from the pellet before it vaporizes. Because the heat needed to vaporize H_2 is 8.5 times the heat needed to only melt it, a melting but not vaporizing pellet will require a much lower heat input to ablate.

For a 1-mm diam ($2r_P$) pellet moving at $v_P = 1$ km/s ($M = 3$) in 1 atm of air, the heat release in watts of condensation will be

$$\dot{Q}_c = v_p\left(\pi r_p^2/2\right)\rho_s\left(Q_{\mathrm{va}} + c_{\mathrm{Pa}}\Delta T_a\right) = 1.8 \times 10^3 \text{ W}$$

where ρ_s is the density behind a $M = 3$ normal shock, Q_{va} is the heat of condensation of air, c_{pa} is its specific heat, and ΔT_a the difference between the air temperature behind the shock and its condensation temperature. For this calculation, T_a is assumed to be that behind the normal shock: 800 K. The particle frontal area has been decreased by a factor of two to account for shrinkage as it ablates. Note that four-fifths of the condensation heat results from cooling the gas.

A minimum lifetime for a particle of mass m_p is then estimated as

$$t_p = (m_p)(\rho_{\mathrm{H}_2})(Qv_{\mathrm{H}_2})/\dot{Q}_c$$

For a particle that sheds liquid with insignificant vaporization, $t_p = 1.5$ μs. If the ablation process vaporizes the particle totally, then the minimum particle lifetime is $t_p = 13$ μs. Both of these times are extremely short. For the real ablation case, a significant part of the incoming heat simply flows by the particle without being transferred due the insulating effect of vaporization from the particle, and a significant part of that heat is absorbed by vaporization, so that the actual ablation lifetime is longer.

An upper limit on supersonic particle ablation can be obtained by combining the estimated heat flux to the particle (on the order of 10^6 W/m^2) with the heat flux required by vaporization mass flux assuming that no liquid is lost. The area of the pellet, including its side, is 5×10^{-5} m^2, so the heating rate of the pellet would be 50 W, and the heat to melt and vaporize is 5.1×10^5 J/kg. The vaporization rate in kilograms per second would then be

$$\left(\frac{\mathrm{d}m}{\mathrm{d}t}\right)_{\mathrm{vap}} = 10^{-4} \text{ kg/s}$$

Because the pellet mass is 4×10^{-6} kg, the pellet lifetime would be about 40 ms. If the pellet were spherical with the same diameter (3.2 mm), its lifetime would be 15 ms. This lifetime would be further reduced if a significant mass of the pellet was ablated by liquid shedding.

This lifetime estimate can be checked for consistency in a number of ways. The heating rate derived if all of the heat in the gas column in front of the pellet was deposited on the pellet is 6.5 kW, which implies that under 1% of this energy actually diffuses to the pellet. This number is consistent with a diffusion calculation that indicated 0.4% of the mass diffused toward the surface.

The flow rate of the mass in the boundary layers around the pellet should also be consistent with this. The hydrogen gas volume flow rate at the edge of the pellet is

$$\frac{\mathrm{d}_{Vg}}{\mathrm{d}t} = (\delta_g)(\pi d_p)(v_l)$$

For a boundary layer thickness of 10 μm at the edge of the pellet, and a velocity of 300 m/s, the volume flow rate in cubic meters per second is

$$\frac{\mathrm{d}V}{\mathrm{d}t} = 3 \times 10^{-5} \text{ m}^3/\text{s}$$

The layer is assumed to be H_2 at 100-K average temperature, and an average pressure of 5 atm behind the shock, which gives a gas density of 1.2 kg/m^3. This density implies a mass flow rate in kilograms per second of

$$\frac{\mathrm{d}m}{\mathrm{d}t} = 4 \times 10^{-5} \text{ kg/s}$$

and because the pellet mass is 4×10^{-6} kg, the lifetime of the pellet will be on the order of 100 ms based on the gas flow at the edge of the pellet. More gas is added from ablation along the sides, leading again to a 40-ms pellet lifetime estimation without including liquid entrainment. Numerous routes result in an estimation of the lifetime of the experimental pellet to be on the order of 40 ms, and the lifetime of a 1-mm-diam pellet to be on the order of 10 ms.

The volume flow of liquid in a 1-μm-thick layer was calculated to be 10^{-7} kg/s. For a liquid density of 73 kg/m^3, the mass flow would be 10^{-5} kg/s, meaning one-quarter of the gas mass flow. This is again consistent and implies that the liquid flow is a significant contributor to ablation.

The wide range in parameters that are appropriate to the problem of hydrogen pellet ablation arise from 1) that all three phases of hydrogen are involved, 2) that the temperature varies from 5–10 K inside the solid pellet to 2000 K in the combustion gas, and 3) differences in the physical properties of hydrogen and the combustion gas. H_2 is an unusually light and small molecule that has a high thermal velocity and a low viscosity of both the gas and the liquid. The thermal diffusivity of H_2 gas varies by a factor of 100 over the mixing zone, as does its momentum diffusivity. Mass diffusivity D varies as

$$D = D_0(T/T_0)^{1.75}(P_0/P)$$

which also varies by a factor of 100. Diffusion next to the solid is small compared with that near the N_2, but both play an important role.

Because the Prandtl number is approximately 0.7 for both H_2 and N_2 at all relevant temperatures, the relative growth rate of velocity and temperature boundary layers remains the same. For H_2 relative to air, their viscosity ratio is about 2 and their density ratio is 15; these ratios are approximately constant with temperature.

Single-Pellet Injection

Single-pellet modeling was undertaken to predict experimental behavior. The solid hydrogen pellet parameters are determined by the preexisting pellet injector as

$$d_p = 3.0 \times 10^{-3} \qquad (3\ \text{mm})$$

$$l_p = 6.0 \times 10^{-3} \qquad (6\ \text{mm})$$

$$T_p = 7, \qquad v_p = 1.0 \times 10^3\ \text{m/s}$$

The pellet is a right circular cylinder of diameter d_p in meters, length l_p in meters, temperature T_p in degrees Kelvin and velocity v_p in meters per second. Subsidiary parameters are a pellet frontal area $A_{\text{fp}} = 8 \times 10^{-6}$ m^2, pellet volume $V_p = 4.8 \times 10^{-8}$ m^3, and pellet mass m_p of 4.2 mg (4.2×10^{-6} kg).

The supersonic pellet entering the gas acts as a blunt body in a supersonic flow. There is a leading normal shock ahead of the pellet and a shock wave along the side of the pellet, diverging at an angle. At the front of the pellet is a high-temperature and high-pressure stagnation region heated by the shocked flow. The flow reaccelerates from that region around the nose of the pellet, becoming supersonic again and expanding around the edge of the pellet, then flowing along the side of the pellet.

For an $M = 3$ flow around a fixed, inert, spherical body, a thin standing shock wave will occur in front of the body at a distance of about 0.18 times the radius of the sphere. For the pellet experiment, the pellet speed into the room temperature nitrogen is 1 km/s, giving a Mach number of 3, but from there, ablation analysis diverges from that of a solid body because of the gas evolving from the heated solid hydrogen pellet. It is useful to pursue further the inert body flow analysis, however, to formulate the freestream constraints on the vaporizing pellet.

The gas is heated and compressed across the shock; the temperature increases by a factor of 2.7, the density by 3.9, and the pressure by 10.3. The pressure varies by ±70% of the dynamic head (about 5 atm) around the body.

The existence of absolute low temperatures leads to the most important difference between solid H_2 and normal ablation. In common ablation, temperatures vary from 300 K in the freestream to 2000 K at the ablating surface. Behind a $M = 3$ shock in standard temperature and pressure [(STP) 273 K at 1 atm] air the temperature is on the order of 800 K, so that there is a temperature ratio of 2.5 between the flow next to the body and a body at STP. In the case of solid H_2, the temperature varies from 800 K (without combustion) to 30 K, the boiling point of H_2 at 4-atm pressure. This represents a temperature ratio of 27. The importance of this difference in temperature ratio across the layer is that all of the diffusion coefficients vary as T^2. For high temperature ablation, T^2 is a factor of 6, where the slowest diffusion is at the freestream edge of the layer. In the case of solid hydrogen, T^2 is a factor of 730, and another factor of 10 higher in a combustion-heated atmosphere. This means that the entire ablation process in the gas phase is rate limited by diffusion in the cold regions near the surface. Also note that the gas species diffusion ends at a temperature of 95 K for nitrogen, a factor of 3 higher temperature than the liquid H_2 temperature and a factor of 10 higher diffusivity than at the surface.

For the pellet injection experiment, the pellet has a 1.6 mm radius and the shock separation is about 0.3 mm. The Reynolds number based on freestream velocity, sphere radius, and density and viscosity behind the shock is about 10^4, so that the boundary-layer thickness without added flow would be on the order of 0.01 mm thick, or 10 μm. Both the gas and liquid boundary layers are extremely thin. There is also a well-defined temperature boundary layer coexisting and superimposed on the momentum boundary layer and of similar dimension. Heat transfer to the wall is determined by the difference between the actual wall temperature and the adiabatic wall temperature. In high-speed flows, the adiabatic wall temperature is significantly above the freestream flow temperature with the added contribution of the stagnation temperature of the flow. Heat transfer correlations based on Nusselt number are used to provide an average heat transferred over the entire surface.

In the gas diffusion layer, the temperature is also varying from 800 K in the freestream (2000 K in the combustor) to approximately 95 K, the condensation temperature for nitrogen at 5 atm. This is a temperature change of a factor of 9, which leads to a density diffusivity product change of a factor of 5, and implies that the rate-limiting region for diffusion is the cold region. The mass flux in kilograms per square meter per second approaching the pellet as a result of the velocity of the pellet is

$$\dot{m}/A = 10^3\ \text{kg/m}^2\text{s}$$

This implies that 0.4% of the incoming gas is condensed near the hydrogen pellet.

The liquid H_2 layer on the pellet flows around the nose of the pellet. The relative speed of the liquid layer relative to that of the gas is determined by the ratio of dynamic pressures, which means that the velocity difference is the square root of the density ratio. This ratio is about a factor of 20, so that if the gas boundary layer moves at an average of 300 m/s, the liquid layer will be moving at about 15 m/s. If the hydrogen liquid film is 1 μm thick, the volume flow rate at the edge of the pellet is 10^{-7} m^3/s.

Heat transfer is critically important because it determines not only the overall ablation rate of the H_2 but the flows around the pellet as well. For a chamber with a nominal length of 1 m, the pellet will displace a column of gas 1 m long and 3.2 mm in diameter, or 8×10^{-6} m^3 of gas. The density of the N_2 gas at 1 atm is about 1 kg/m^3, so that the mass of gas in the displaced column of gas is 8×10^{-6} kg, and the gas temperature is 800 K. The heat in the column in joules (based on heat capacity) is

$$Q = 6.5\ \text{J}$$

Thus, if all of this heat were absorbed into the pellet, it would be fully vaporized in a pathlength of about 30 cm, or simply melted in about 4 cm. Most of this energy flows around the pellet; only a small fraction diffuses to the liquid surface to melt the pellet. In terms of the heating rate, the pellet passes through the 1-m column in 1 ms, so that the potential heat deposition is 6.5 kW.

Heat Transfer Calculations

Heat transfer calculations are done in terms of correlations for the adiabatic wall temperature, the recovery factor, and the Stanton number, all as functions of the wall injection rate, for a variety of gas pairs, including H_2–air and H_2–N_2 (Ref. 10). Also given are correlations for the wall concentration of injected gas, and this can be used fairly directly to tie to the vaporization rate, by imposing the condition that the wall pressure of the injectant is the equilibrium vapor pressure at the assumed liquid surface temperature (and then iterating on that temperature to satisfy the surface heat balance). In the case of hydrogen pellet ablation, the correlations are distorted in ways that are difficult to predict as a result of changes in constant parameters and the condensation heat release.

Mathematically, the problem is approached by matching heat fluxes at the boundaries of the regions and trying to determine the layer thicknesses that allow consistent matches throughout the volume. One way to estimate the heat transfer is to assume pure conductive heat transfer over an appropriate layer thickness. The conductivity would be determined at the average temperature, and the temperature difference would be determined across the diffusion limited section of the layer.

Assume a temperature gradient thickness δ of 10^{-6}, a thermal conductivity k of H_2 at 50 K of 0.04 W/m-K: A temperature difference of 50 K gives a heat transfer rate in watts per square meter of

$$\dot{Q} = k\Delta T/\delta = 2 \times 10^6 \text{ W/m}^2$$

The heat transfer to the H_2 liquid layer is another controlling parameter for the overall pellet ablation.

The heat transferred through the liquid layer determines the melting rate of the solid, which determines the regression rate of the pellet surface. The melting heat flux at the bottom of the liquid layer is a relatively small factor in the heat transfer problem, however, because the heat of vaporization is so much larger than the heat of fusion. The heat of fusion, however, would be a limiting case if most of the liquid is carried off the pellet by fluid dynamic forces rather than being vaporized.

The regression rate of the melt–solid interface is

$$\frac{\mathrm{d}x_s}{\mathrm{d}t} = \frac{(\dot{Q})(A)}{(Q_m \rho)}$$

The heat flux $\dot{Q}$ through a layer of thickness t_{lH} of liquid H_2 is

$$\dot{Q} = k_{\mathrm{lH}} \frac{\mathrm{d}T}{\mathrm{d}x}$$

The thermal conductivity of liquid H_2 is $k_{\mathrm{lH}} = 0.11$ W/m · K, which is low for common liquids. Assume a linear temperature gradient through the liquid layer, the freezing (14 K) and boiling temperature (30 K), the heat flux in joules per square meter per second is

$$\dot{Q} = 1.7/t_{\mathrm{lH2}}$$

where t_{lH} is in meters. Assuming a liquid layer thickness on the order of 1 μm implies a heat flux of

$$\dot{Q} = 1.7 \times 10^6$$

which is on the same order as the heat flux calculated through the gas layer.

The maximum temperature gradient possible through the gas layer above the liquid layer is a linear gradient between the boiling temperature at 1 atm (20 K) and the condensation temperature of the combustion gas, taken to be 50 K. (Significant subcooling is expected to take place.) The maximum heat flux is, thus,

$$\dot{Q}_{\max} = 0.9/t_{g1\mathrm{H}} \text{ J/m}^2\text{s}$$

where $t_{g1\mathrm{H}}$ is in meters. For $k_{\mathrm{H}g} = 0.030$ W/m · K. Thus, the gas layer that extends from 20 to 50 K in the gas temperature diffusion profile of hydrogen must also be on the order of micrometers thick to melt the pellet.

The maximum temperature gradient possible through the interdiffusing gas layer above the hydrogen gas layer is a linear gradient between 50 and 2000 K. The maximum heat flux is

$$\dot{Q}_{\max} = 200/t_{g2\mathrm{H}}$$

where $t_{g2\mathrm{H}}$ is in meters. For $k_{\mathrm{H}g} = 0.1$ W/m · K because the thermal conductivity of H_2 gas is a factor of 10 more than that for N_2. Thus, the outer gas layer can be a factor of 200 thicker and still transmit the same amount of heat through the two thin layers near the pellet.

The timescales of the pellet experiment are such that transient effects add complications to the analysis of pellet heat flows. A pellet traveling at a speed of 1 km/s will only require 1 ms to travel 1 m. Thus, the first 10 cm of travel into the N_2 only requires 0.1 ms. At room temperature, diffusivities D in nitrogen are of the order of 10^{-4} m^2/s and vary as the square of the temperature. (Mass, momentum, and thermal diffusivities are similar.) Diffusion times over a length scale d are on the order of d^2/D, such that a temperature gradient on the scale of 0.1 mm (one-third of the shock standoff distance) will require 0.1 ms to diffuse. The full gas boundary layer is 30 μm thick and the cold part 10 μm thick. At the bottom of the H_2 gas layer, the temperature is a factor of 27 lower, and the diffusivity has decreased by a factor of 700, so that the diffusion time for the cold bottom of the boundary layer will be a significant fraction of the residence time period of the pellet. The flow over the pellet has a residence time on the order of 0.01 ms, so that the shock flows are well established very quickly.

One interesting aspect of this transient diffusion is that the gas condensation occurs at 77 K and, thus, is not slowed down by the very low-temperature diffusion region next to the pellet.

It is not clear that there is actually time to condense the freestream gases near the pellet. Because the residence time of the cold gases near the pellet deep in the boundary layer will be on the order of 0.1 ms, and the collision rate is very high, it is believed that condensation will probably occur. However, there are questions of nucleation, subcooling, and the number of collisions required to condense that should be investigated.

Based on the thermal diffusivity, $\alpha_{Hp} = 8.14$ cm^2/s of paraH_2, thermal time constant for propagating a thermal pulse through 1 mm of solid paraH_2 is about 1 ms. For the dynamic problem, these diffusion times are irrelevant because the liquid is stripped away.

The pressure must be such that the pressure must not change by more than shear strength of solid H_2 (5 atm) over the length scale of the pellet, otherwise the pellet would be squashed by the pressure.

Experiments

Defining reasonable (moderate difficulty, moderate expense) experiments that would allow the measurement of the ablation rate of a solid H_2 particle is a difficult task. A H_2 slurry fuel must first have some form of experimental support for the practicality of the technique to justify slurry fueling experiments in a vehicle or in a scramjet test facility.

A laboratory experiment was conceived and designed based on firing a H_2 pellet at high speed into a gas reservoir using an existing fusion plasma fueling injector.[11] Instantaneous high-speed photographs allow the ablation rate to be estimated based on the change in the pellet shape and the ablation plumes. These experiments, subcontracted by Thoughtventions to the University of Illinois at Urbana–Champaign, were informative but not conclusive, weakened by poor fluid mechanics experimental technique. These experiments are discussed in more detail elsewhere.[12] Using a shock tube has been considered, but injecting a pellet into the supersonic stream after the initial shock and debris passage would be just as difficult as the technique attempted.

For the experiments performed, cylindrical solid hydrogen pellets, 3.2 mm in diameter and 6 mm long at a temperature of 6–8 K, were injected at a speed of approximately 1 km/s into a pressurized chamber filled with inert gas at a speed of approximately 1 km/s. The pellets were imaged through a window at 17 cm and 79 cm from the end of the injector tube to examine the processes of pellet ablation. Pellet acceleration was done using a single-stage light gas gun using 65.80 atm of driving gas.[11]

Because the pellet injector must operate in an atmosphere of low pressure of helium to minimize heat transfer, the primary problem in using it for ablation studies has been the transfer of the pellet to the pressurized test chamber without pressurizing the injector itself, which would lead to warm up and prevent further pellet production. Inadequate pump capacity prevented use of a graded gas/vacuum interface through a series of chambers. The pellets were also found to be too weak to penetrate a thin aluminum foil diaphragm. A fast valve between the injector and chamber was considered, but all commercially available valves are too slow.

Finally, it was decided to pressurize the ablation chamber using a fast gas valve. A coupling chamber was used to dissipate the high-pressure pulse behind the pellet that accelerates it. The ablation chamber was filled to a fraction of an atmosphere pressure in a fraction of a second, at which point the pellet was fired before it could melt. The pellet apparatus and ablation chamber were then pumped down and the process repeated. The program duration was such that 1-atm room temperature injection was not achieved. Injection was performed into N_2 and into He rather than air to avoid the possibility of combustion. Injection into He was done to determine if N_2 condensation was a major effect.

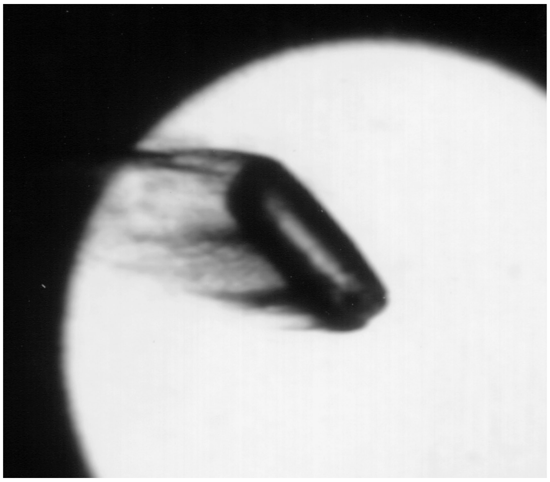

Fig. 4 Pellet injected into 0.32 atm of N_2, 79 cm from entry into ablation chamber showing maximum ablation.

The goal of the ablation experiments was to ablate a significant fraction of the pellet and, thereby, determine the conditions and time that account for this ablation. If the pellet was totally ablated before it reached the imaging port, experiments could be performed at lower temperature and pressure. If no pellet ablation was apparent, the gas pressure and temperature could be increased, allowing iteration to determine actual estimated pellet ablation time at different conditions. The pellets, pellet speed, and the imaging system were nominally the same for all of the data; each image was of a separate pellet. The vacuum injection images showed a basic, consistent shape of the pellet, seen as a right circular cylinder with fairly flat ends. The pellets were tumbling, presenting different perspectives of each pellet in each image and indicating that there was no steadily ablating front of the pellet.

Images of pellet injection into N_2 were taken at 0.23- and 0.32-atm pressure and at He pressures of 0.43 and 0.87 atm. Gas temperature was unknown due to expansion cooling, but was estimated to be 150 ± 50 K. Figure 4 shows an image of one of the highest ablation rate cases, where the pellet was injected into a pressure of 0.32 atm of N_2, 79 cm from its entry into the ablation chamber.

All of the shock parameters depend only on M. The pellet velocity is fixed at approximately 1 km/s, but the speed of sound varied, as did the pressure, significantly changing ablation parameters. The speed of sound in N_2 at 300 K is 353 m/s and is 2.9 times larger in He. If the ablation gas had been at room temperature, the pellet would have $M = 2.8$ in N_2 and approximately 1 in He. For the flow-cooled gases with a temperature of 150 K as already discussed, the Mach numbers are 4 for N_2 and 1.4 for He.

For a $M = 4$, N_2 flow, the density ratio ρ_r across the shock is 4.6 and the temperature ratio T_r is 4.0. For helium at $M = 1.5$, ρ_r is 1.7 and the temperature ratio T_r is 1.5. Because the experimentally achieved pressure of the N_2 in the ablation chamber was about one-half that of the He, and the density of He was one-seventh that of N_2, the resulting density of the N_2 at the nose of the pellet was 9.5 times that of the He. The relative gas enthalpy is the ratio of $\rho c_p T$ for each gas; the specific heat of He is five times that of N_2. This implies that the N_2 had five times the enthalpy behind the shock as did the He. Balancing this heat source and the heat source of N_2 condensation is that the thermal conductivity of He gas is 5.4 times that of nitrogen. The thermal diffusivities of the two gases are approximately the same, so that the time to heat the pellet should have been about the same.

The data show much more ablation for the N_2 than the He, as indicated by greater or lesser plumes of black ablation residue as seen in Fig. 4. This is true even though the N_2 pressures were half that of the He One explanation of this difference would be the condensation heat release of the N_2. The earlier argument tends to indicate that this is the case, but the larger enthalpy of the N_2 may also be a significant factor. Furthermore, the Reynolds numbers in N_2 are a factor of seven higher than He, leading to greater heat transfer.

The shock standoff distance in front of the pellet at 1 atm is only 0.3 mm at Mach 3; this is below the resolution of the imaging for a pellet with a spherical nose.

The tumble probably has a significant effect on whether the edges of the pellet are rounded as a result of ablation. The case where the pellets present their side to the flow is much more dynamically stable and is the case usually seen. It is also a case where the sharp edges will tend not to become rounded.

Rounding of the edges of the pellet can be used to derive an ablation rate and heating rate. Assuming an ablation rate of about 0.3 mm in 0.5 ms implies a regression rate of 0.6 m/s, which would imply that the lifetime of a 1-mm spherical particle would be on the order of 1 ms. This is probably an underestimate as a result of high heat transfer at the edges of the pellet. This implies a heat flux on the order of 10^7 W/m^2, which is consistent with ablation modeling of a spherical particle that predicts a minimum heat transfer rate on the order of 10^6 W/m^2, even at the reduced temperatures and densities of these experiments.

Ablation is much greater for injection into nitrogen as compared with helium. The ablation is clearly strongly dependent on fill pressure, although this difference in fill pressure may have caused a temperature difference as well as a pressure difference in the ablation chamber. The experiments support a lifetime of less than 10 ms for a 1-mm particle in an $M = 3$ flow.

One very interesting aspect of the images with respect to hydrogen mixing is that the liquid hydrogen in the pellet wake always disappears within a distance of one pellet diameter or less. This is very rapid vaporization and is consistent with high heat transfer to very small droplets. It also implies that mixing of the freestream gas with the hydrogen is primarily gas-phase mixing of the wake. There is no question, however, that liquid shedding is a major phenomenon in solid H_2 ablation.

Conclusions

Modeling and experiments have been performed to demonstrate that a wall-injected solid hydrogen/liquid helium slurry is a practical and attractive technique for scramjet fueling. Solid hydrogen slurry fueling has the following crucial advantages: 1) The wall injected solid can penetrate the high-speed flow over the full width of the combustor. 2) Protruding injector losses are eliminated. 3) Gas and liquid shedding from the moving solid cause extremely fast volumetric mixing such that combustion can be completed within the engine. 4) CSAs to the solid hydrogen can enhance energy release or catalyze combustion. The slurry fuel can be pumped and stored as a standard liquid.

Critical aspects of the concept are the physical properties that are unique to hydrogen and that lead to extremely fast particle ablation: low liquid viscosity, the low absolute temperature of the solid, and condensation of the freestream gases near the pellet. Large temperature gradients and condensation of air near the solid, in turn, cause a large heat release for ablation that does not occur for any other ablating material. Furthermore, the surface tension of hydrogen liquid is so low that liquid entrainment dominates ablation rather than vaporization, greatly lessening the overall heating requirements of ablation. The entrainment of gas eddies and very small droplets of hydrogen liquid from the solid provide dispersed volumetric mixing with the air as the particles pass across the combustor volume.

The solid hydrogen particles must penetrate the flow and travel across the full width of the combustor for efficient combustion. This requires an injection velocity and a particle size that are larger than a specified minimum. A solid hydrogen particle must have a diameter of at least 1 mm for it not to lose so much of its 100 m/s cross-flow velocity that it will not travel the 1 m across the combustor in the approximately 10-ms residence time. Modeling of the fluid mechanics of solid hydrogen particle ablation implies a 10-ms maximum ablation time for a 1-mm-diam hydrogen particle implying adequate ablation times in the worst case. The particle size and injection velocity can be adjusted to achieve the desired penetration and dispersion of fuel within the combustor.

Experiments were performed that imaged a 3-mm-diam solid H_2 pellet injected into vacuum, He, and N_2 at a speed of 1 km/s. These ablation images showed that significant liquid shedding had already begun on a timescale of 0.1 ms and that ablation occurred in proportion to temperature and pressure of the gas. The short residence time of the pellet (1 ms) and the low pressures and temperatures of the experiments (relative to realistic scramjet combustor conditions) prevented ablation of a measurable fraction of the pellet, so that experimental limits on mass ablation rates could not be determined.

Whereas modeling and experiments imply rapid ablation rates, neither conclusively demonstrate that solid hydrogen particle ablation is rapid enough to make solid hydrogen liquid helium slurry fuelling a practical scramjet fuelling technique.

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