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Technical Notes

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Laser–Air Interactions in an Internal Supersonic Flowpath

Robert B. Adams*
International Space Systems, Inc., Huntsville, Alabama 35816
and
D. Brian Landrum†
University of Alabama in Huntsville, Huntsville, Alabama 35899

Introduction

A NOVEL airbreathing propulsion system using a fusion power source has been proposed.[1] This system, referred to as the simultaneous heating and expansion (SHX) engine, uses fusion reactor driven lasers to heat the air in the engine flowpath. The heated air is then expanded for thrust. To assess performance the complex interactions between the laser beams and the working air must be accurately modeled. This Note describes an iterative technique that models both the airflow and beam properties throughout the engine flow path.

Airflow Model

The combustor and expansion sections are divided into differential volumes, as illustrated in Fig. 1. The interface between each volume is called a node. The flow is assumed to be steady, inviscid, supersonic, and quasi-one-dimensional with heat addition. Body forces are neglected. Derivations of the governing equations for conservation of mass, momentum, and energy with these assumptions can be found in most classical textbooks.[2,3] When sufficiently small differential volumes are assumed, a linear relationship between pressure and area replaces the pressure integral in the momentum equation. The resultant governing equations for the gasdynamic properties in a differential volume of axial length Δx are

$$\rho_x u_x A_x = \rho_{x+\Delta x} u_{x+\Delta x} A_{x+\Delta x} \tag{1}$$

$$\rho_x u_x^2 A_x + p_x A_x + [(p_{x+\Delta x} + p_x)/2](A_{x+\Delta x} - A_x) = \left[\rho_{x+\Delta x} u_{x+\Delta x}^2 A_{x+\Delta x} + \cdots + p_{x+\Delta x} A_{x+\Delta x}\right] \tag{2}$$

$$h_x + u_x^2/2 + q = h_{x+\Delta x} + u_{x+\Delta x}^2/2 \tag{3}$$

where u is the air velocity, ρ the density, p the pressure, A the engine duct cross-sectional area, h the specific enthalpy, and q the heat addition per unit mass.

There are four unknown variables, u, ρ, p, and h, in Eqs. (1–3). Therefore, an equation of state must be included to solve the equation set. The SHX model assumes either frozen or equilibrium chemistry to calculate the air properties. The frozen flow equation of state is

$$p = \rho R T \tag{4}$$

where T is the gas temperature and R the specific gas constant. For frozen flow, both R and c_p, the specific heat at constant pressure, are constant. The values of c_p and R are variable in equilibrium flow. Anderson[4] describes several methods to model the equation of state for an equilibrium flow. The model used in this analysis is a series of polynomial correlations developed by Tannehill and Mugge[5] to express the enthalpy of high-temperature air as a function of pressure and density,

$$h(p,\rho) = \frac{\tilde{\gamma}(p,\rho)}{\tilde{\gamma}(p,\rho) - 1} \tag{5}$$

where $\tilde{\gamma}(p,\rho)$ is a polynomial with coefficients that are functions of the pressure and density range. Based on a specified geometry and heat addition per unit mass, the set of Eqs. (1–4) or (5) are solved at each node to calculate the flow properties through the engine.

Beam Model

The SHX concept uses laser beams to heat the ingested air. Merkle[6] modeled the relationship between the laser beam parameters and the rate of energy deposition to the air by

$$h^0_{\text{final}} - h^0_{\text{initial}} = q = I\alpha\Delta s/\rho u A_{\text{beam}} \tag{6}$$

where h^0 is the total enthalpy per unit mass, I the total power delivered by the laser beam, and A_{beam} the cross-sectional area of the beam. The absorption coefficient α is the fraction of energy absorbed per unit length of gas Δs, through which the beam traverses.

A laser beam traveling through a representative control volume would heat only a portion of the air. Therefore, in a real system, multiple beams would be projected through the volume at different angles to meet the heating requirements of the propulsion system. The SHX model assumes that the sum of all of the beams' energy is dispersed uniformly over the engine duct's cross-sectional area at every point in the flow [$A_{\text{beam}} = A(x)$]. Consistent with this assumption, the beam path distance Δs is assumed to be equal to the volume length Δx.

Injected energy beams could potentially reflect off of the engine walls. An analysis by Brown et al.[7] suggests that heating produces a high-density gradient in the wall boundary layer. This gradient refracts the laser beam before it reaches the wall. Therefore, laser heating of the engine walls is neglected in this analysis.

The beam power attenuation is determined by the air's absorption coefficient and the path the beam takes through the gas,[7]

$$\frac{\partial(I/A_{\text{beam}})}{\partial s} = -\alpha\frac{I}{A_{\text{beam}}} \tag{7}$$

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*Systems Engineer, 500 Wynn Drive, NW, Suite 306; currently, NASA Marshall Space Flight Center, Huntsville, AL. Member AIAA.
†Associate Professor, Department of Mechanical and Aerospace Engineering, Propulsion Research Center, Tech Hall S234. Senior Member AIAA.

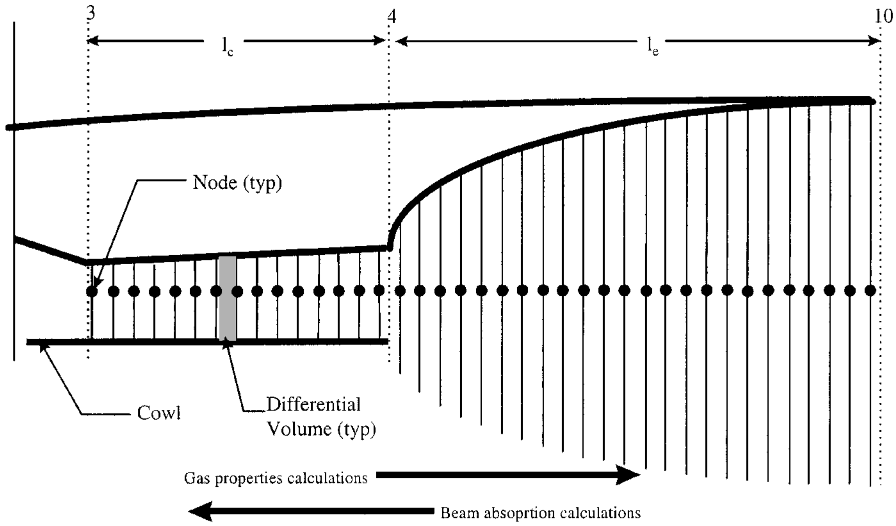

Fig. 1 SHX engine flowpath showing differential volumes.

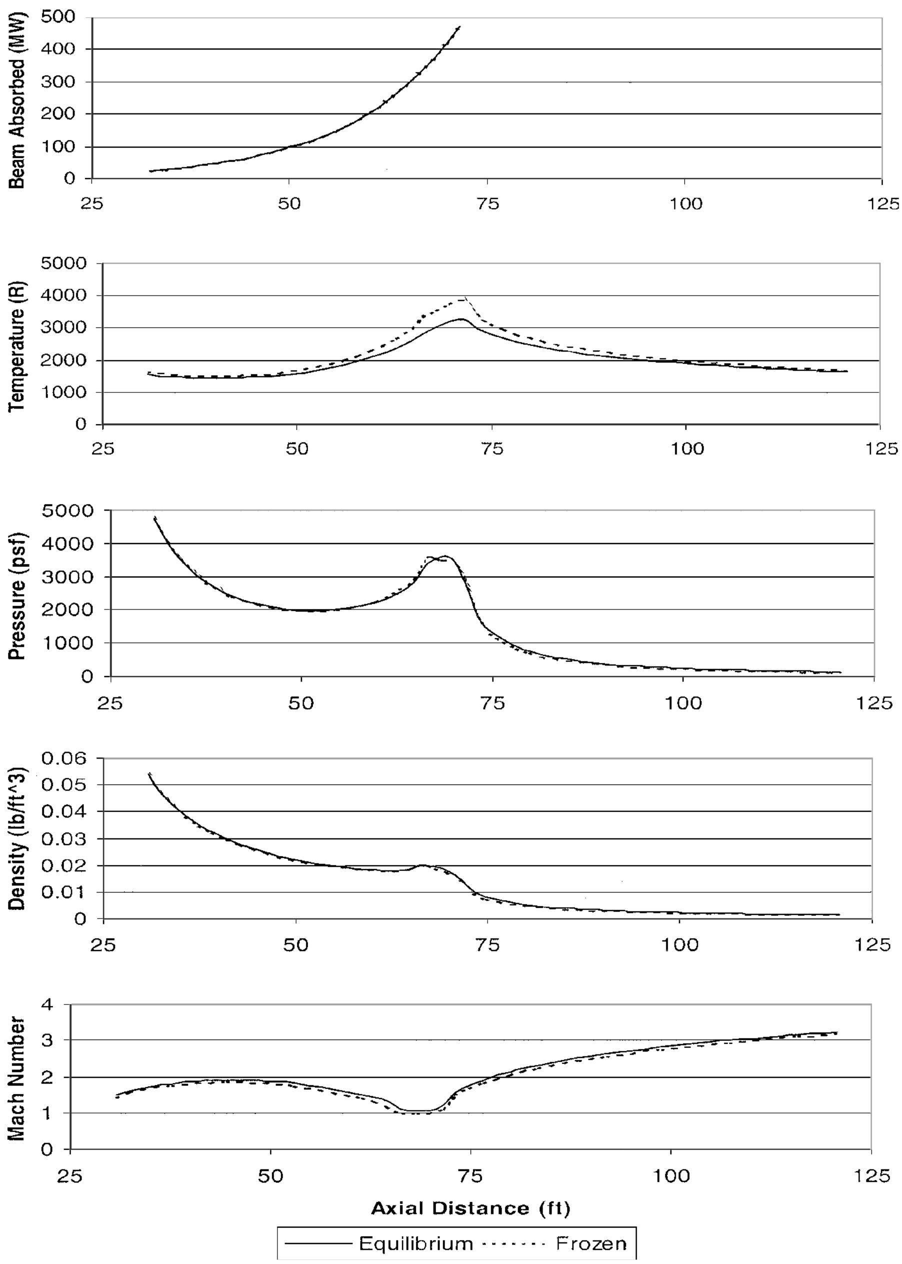

Fig. 2 Calculated axial property profiles for frozen and equilibrium flow in an HF laser heated SHX engine.

Equation (7) can be rewritten in finite difference form for a differential volume. Combining the resultant equation with Eq. (6) and assuming $\Delta s \approx \Delta x$ and $A_{\text{beam}} \approx A$ yields a relationship between the beam attenuation and the gas heat addition per unit mass

$$q \approx \frac{I_{x+\Delta x} - I_x}{\rho_x u_x A_x} \tag{8}$$

The axial area profile $A(x)$ must be specified for a given engine duct. The gasdynamic and beam equations are related through the heat input variable q and the absorption coefficient α, which tends to be a function of the local density. The SHX engine model assumes that the beams are located at the downstream end of the combustion chamber and projected forward (upstream). Because the engine airflow is completely supersonic, flow calculations must proceed moving downstream. However, the nature of beam attenuation requires that the beam absorption profile be calculated moving upstream. To resolve this dilemma, the code calculates the gasdynamic properties by solving the conservation equations and equation of state simultaneously, with a uniform heating profile based on the total beam energy available. A new heating profile is determined using the beam attenuation equations. The new heating profile is then used to again solve the conservation equations. This iterative process continues until the heating profile converges to a predetermined level.

Model Calibration

Several techniques were used to assess the accuracy of the SHX model calculations. Simulations were run assuming frozen flow, first with an area change and no heat addition (isentropic flow) and then with a constant area with simple heat addition (Rayleigh flow). The calculated results were compared to closed-form equations for isentropic and Rayleigh flow from Ref. 2. The SHX calculated isentropic flow properties were within 1% of the expected values.

For the Rayleigh flow calculations the total heat input was limited to 100 MW to prevent thermal choking. The frozen flow Mach numbers along the duct were within 1% of the Rayleigh flow values. An equilibrium flow simulation was also run for this heat input. Although the shape of the axial Mach number profile was almost identical, the calculated equilibrium flow values were approximately 4% higher than the frozen flow Rayleigh values. The temperature for these conditions ranged from 1500 to 1800°R (833 to 1000°K). Air in this temperature range will experience excitation of vibrational modes, which affects the ratio of specific heats and, thus, the flow property calculations. Therefore, the profile differences can be explained by the equilibrium calculations taking vibrational excitation into account, whereas the Rayleigh flow calculations do not.

The authors also assessed mass, momentum, and energy conservation between the engine duct inlet and expansion outlet. As expected, the error between the computed input and output values decreases as the number of calculation nodes (or differential volumes) increases. The number of nodes used for the final simulations was selected to maintain the total change in conserved properties at less than 1%. The difference between total heat input calculated from the gasdynamic property changes and the beam model was also maintained at less than 1%.

Sample Results

An SHX engine simulation was performed to illustrate typical model predictions. The simulation assumed a flight speed of Mach 5.0 at an altitude of 65,750 ft (20,040 m). The airflow passed through a bow shock generated by a wedge-shaped forebody with a 25-deg half-angle. The flow was then turned back 25 deg through an inlet shock so that it was parallel to the engine duct. Consistent with the station nomenclature shown in Fig. 1, the combustor length was $l_c = 40.0$ ft (12.2 m). The combustor inlet height and width were 3 and 12 ft (0.91 and 3.66 m), respectively. To alleviate thermal choking, the combustor duct expanded with an area ratio of $A_4/A_3 = 3$. The combustor flow exits to isentropic expansion surface with a length of $l_e = 50$ ft (15.2 m). The expansion had an area ratio of $A_{10}/A_4 = 4$. The cross-sectional area profiles varied linearly with axial distance along the duct.

A hydrogen–fluorine (HF) laser located at the combustor exit was used to heat the airflow. The beam intensity of the laser at the combustor inlet was 4000 MW. As described in Ref. 1, an HF absorption coefficient was derived as a function of density $\alpha(\rho)$ from the radiatively driven wind-tunnel data presented in Ref. 7.

The calculated axial property profiles and computed energy absorption for this SHX engine simulation are shown in Fig. 2. Both frozen and equilibrium flow calculations are shown. The "knuckle" evident at 70 ft (21.3 m) for all of the properties in Fig. 2 is at the interface between the combustor and expansion sections. The HF laser beam is fired at this interface toward the front of the combustor duct. No heating occurs in the expansion section. The increasing area and low energy absorption cause the flow initially to accelerate in the combustor. The increased energy absorption near the combustor exit then drives the flow toward a thermal choke ($M = 1$). At this point, the heat input goes to zero, and the slope of the area profile changes. The Mach number increases rapidly in the expansion section, where there is no energy input.

The equilibrium and frozen property profiles are similar. The most evident deviation is in the temperature profile. This is expected because the vibrational mode excitation will manifest itself as a reduction in the temperature. The energy required to excite this mode reduces the energy available to transform to kinetic energy. This explains why the equilibrium Mach number profile is slightly lower than that of the frozen flow.

Conclusions

Assessing the performance of future advanced propulsion systems such as the SHX engine requires modeling the complex interactions between the laser beams and the working air. The iterative method presented in this Note reasonably predicts the heating of a supersonic airflow by an HF laser beam. The quasi-one-dimensional model is modular, so that other types of energy beams (laser or microwave) can be simulated. The model can be used for parametric studies to tailor the heating and area change profiles to optimize SHX engine performance.

Acknowledgments

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