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Short communication

Modeling of incomplete combustion in a scramjet engine

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ABSTRACT

In the present study, an empirical theoretical split chemistry model was developed to describe the phenomenon of incomplete combustion for scramjet engines. The model was developed by decoupling flow into two distinct regions, namely, unburned and burned, as in real scramjet flows. The conservation equations for the combustor and the rate equations for the supersonic nozzle were calculated independently for these two regions using the split ratio of the volume occupied by the fuel–air mixture to the overall volume. The split chemistry model was implemented in a one-dimensional flow solver by assuming that the combustion efficiency is known. The effect of incomplete combustion on the performance of a hydrocarbon-fueled scramjet engine was investigated by performing a parametric study along the entire flow path through the scramjet engine, including the inlet, isolator, combustor, and supersonic nozzle. The results showed that, for a combustion efficiency of 0.5 with a global equivalence ratio of 0.5, the overall temperature and the thrust performance along the flow path through the combustor and the nozzle significantly decrease owing to incomplete combustion. It was also observed that the chemical composition of the fuel-only region varies, regardless of the change in combustion efficiency, because efficiency is a function of the extent of the combustion reaction and the split ratio. It was found that the present split chemistry model is useful to describe incomplete combustion, and it can be effectively utilized for the preliminary design and analysis of scramjet engines.

1. Introduction

When a fuel–oxidizer mixture is subject to rapid cooling before the combustion is completed, incomplete combustion is likely to occur. Such a phenomenon is typically observed in supersonic combustion ramjet (scramjet) engines. In a scramjet engine, air moves at supersonic speed inside the combustor and through the supersonic nozzle. The fuel remains inside the combustor for a short duration, and thus, before combustion is completed, the fuel–air mixture may be cooled via expansion in a divergent nozzle.

To prevent incomplete combustion and to enhance combustion, the fuel and air must be mixed at the molecular scale. When the fuel is injected into the air stream in the combustor, the large gaseous bulks of fuel break into smaller ones through turbulent motion. Then, molecular diffusion between the fuel and air occurs across the outer surface of these bulks. From the well-known random walk theory [1], it is known that the depth of penetration of fuel into air is proportional to the square root of the number of molecular collisions. This implies that considerable time is needed for fuel molecules to penetrate bulks of typical sizes. In contrast, heat conduction occurs relatively faster because the extent of heat conduction is directly proportional to the number of molecular collisions. As a result, the bulks of fuel can be heated to a temperature similar to the surrounding air, while the bulks inside may remain only partially air-mixed even when the bulks are discharged into the expanding nozzle. Several studies related to the issue of incomplete combustion have been previously conducted [2–7]. However, there is currently no theory that satisfactorily describes this phenomenon.

In the present study, an empirical-research-based theoretical split chemistry model is proposed to describe the incomplete combustion phenomenon. The model was developed by decoupling the flow into two distinct regions, namely, unburned and burned, as in real scramjet flows. The model was then implemented in a one-dimensional flow solver to solve the conservation equations for the combustor and the rate equations under non-equilibrium states for the supersonic nozzle. The present solver was applied to the preliminary design and performance evaluation of a hydrocarbon-fueled scramjet engine. To investigate the effect of incomplete combustion on the performance of the vehicle, a parametric study was conducted by performing the analysis along the entire flow path through the scramjet engine, including the inlet, isolator, combustor, and supersonic nozzle.

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Nomenclature

A	cross-sectional area	m^2
C_p	frozen specific heat at constant pressure	J/(mol K)
f_a	split chemistry function for fuel-only flow	
f_b	split chemistry function for fuel–air mixture	
h	static enthalpy	J/kg
h_0	energy of formation	J/kg
H	total enthalpy	J/kg
k	Boltzmann constant	J/K
$\dot{m}_f$	fuel flow rate	kg/s
$\dot{m}_\infty$	air flow rate	kg/s
M	molecular weight	kg/mol
NSP	number of species	
N_v	number of molecules	
p	pressure	Pa
r_b	split chemistry parameter	
R_u	universal gas constant	J/(mol K)
T	temperature	K
u	velocity	m/s
V_i	rate of change of vibrational energy σ_i by collisions	J/(kg s)
W_i	rate of production of species i by chemical reactions	mol/(kg s)
X	unspecified third body	
x	distance along supersonic nozzle	m

Greek

ϕ	fuel–air equivalence ratio	
γ_i	species concentration	mol/kg
η_c	combustion efficiency	
η_e	energy efficiency of inlet	
η_i	momentum efficiency accounting for the loss in isolator and fuel injector	
η_m	momentum efficiency of inlet	
ρ	density	kg/m^3
σ_i	vibrational energy of ith mode of vibration	J/kg

Subscripts

1	entrance to combustor
2	exit of combustor
a	fuel-only flow
b	fuel–air mixture
i, j	chemical species index

2. Split chemistry model

2.1. Physics of incomplete combustion

Inside the combustor of a scramjet engine, incomplete combustion may occur. The extent of incomplete combustion is represented by the combustion efficiency, which can be measured experimentally. In the present study, the combustion efficiency was assumed to be a known value.

In the present split chemistry model, the flow path through the combustor and supersonic nozzle is assumed to consist of two regions: one where the fuel and air are mixed and the other with fuel alone. This happens because the fuel and air are not able to penetrate completely into each other. For the fuel molecules to mix with the air molecules to a sufficient extent at a molecular level, mutual diffusion must occur. However, according to the random walk theory [1], the average distance traveled by a molecule in such a diffusion phenomenon is a product of the mean collision distance and the square-root of the number of collisions. Because of this square-root dependence, mixing at a molecular scale takes time. When the flow inside the combustor is subsonic, the molecules reside there for a sufficiently long duration for this random walk to complete. In contrast, when the flow is supersonic, the duration is shorter, and therefore, incomplete combustion may occur.

The average molecular speed, $\sqrt{8kT/\pi M}$, is nearly the same as the speed of sound, and the ratio of the flow speed to the average molecular speed is approximately the flow Mach number. Therefore, for a combustor of fixed length, the extent of combustion can be considered a function of the Mach number. When the flow Mach number inside the combustor is much larger than one, a more incomplete combustion occurs. Once the fuel–air mixture leaves the combustor and enters the expanding nozzle, further molecular diffusion between the fuel and air may not occur because the flow moves faster in that zone.

2.2. Split chemistry parameter

Since the combustion in a partially mixed fuel–air flow is modeled by two distinct flow regions in the present split chemistry model, the chemical changes in these two regions are also calculated independently. The ratio of the volumes occupied by the fuel-only flow and the fuel–air mixture is given by:

$$\frac{\text{Volume occupied by fuel-only flow}}{\text{Volume occupied by fuel–air mixture}} = \frac{\dot{m}_f(1-\eta_c)}{\dot{m}_f\eta_c + \dot{m}_\infty}\frac{\bar{M}_b}{\bar{M}_a} \tag{1}$$

The split chemistry parameter, r_b, is defined as the ratio of the volume occupied by the fuel–air mixture to the total volume:

$$r_b = \left[1 + \frac{\dot{m}_f(1-\eta_c)}{\dot{m}_f\eta_c + \dot{m}_\infty}\frac{\bar{M}_b}{\bar{M}_a}\right]^{-1} \tag{2}$$

The average molecular weights, $\bar{M}_a$ and $\bar{M}_b$, are calculated by

$$\bar{M}_a = \left(\sum_i^{NSP}\gamma_{ai}\right)^{-1}, \qquad \bar{M}_b = \left(\sum_i^{NSP}\gamma_{bi}\right)^{-1} \tag{3}$$

2.3. Conservation equations for combustor

The thermodynamic property values at the entrance of the combustor were first calculated using an ideal inviscid flow approximation. When the angle of attack of the vehicle is zero, the ideal oblique shock wave relations yield these values at the exit of the inlet. For finite angles of attack, the lateral distribution of these properties at the inlet exit can be obtained by performing computational fluid dynamics (CFD) calculations. Then, the properties are integrated over the inlet exit area; the average values can be input into the one-dimensional flow solver as the inflow conditions for the combustor.

For an inviscid flow in the inlet, the surface friction and the heat transfer rates are calculated using the Van Driest formula [8], in which the area-integrated friction force is divided by the momentum flux at the inlet exit to obtain the fractional decrease in momentum due to friction. By subtracting this fraction from unity, the momentum efficiency of the inlet, η_m, is obtained. Likewise, the area-integrated heat transfer rate is divided by the energy flux at the inlet exit to obtain the fractional decrease in energy due to heat transfer. The energy efficiency of the inlet, η_e, is obtained by

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