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Two-phase flow effect on hybrid rocket combustion

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Abstract

This study numerically explores the aerodynamic and combustion processes in a hybrid rocket combustor, under a two-phase turbulent flow environment, considering the evaporation, combustion and drag of droplet and droplet ignition criterion. The predictions of temperature, reaction mode, reactant mass fraction, velocity, oxidizer consumption, fuel regression and droplet number distribution enhance understanding of the two-phase combustion aerodynamics inside the combustor. A parametric study of the inlet spray pattern, including spray cone angle, spray injection velocity and droplet size, is performed to improve the operation of reactant mixing and higher fuel regression rate. Analytical results indicate that both the oxidizer consumption and the fuel regression increase with increasing spray cone angle and spray injection velocity in the practical range of operation. However, for stoichiometric operation, the superior spray cone angle is within 20–60°, and spray injection velocity within 20–40 m/s, under a volume-mean droplet radius of 50 μm. The power dependence of solid-fuel regression on total mass flux is found to decrease with rising of droplet mean size.

Keywords: Hybrid rocket; Spray combustion; Droplet model; Liquid oxidizer

1. Introduction

Hybrid rocket technology has attracted considerable attention in recent decades owing to its ability to combine many technical advantages of both liquid and solid rockets, such as simplicity, safety, restartability and low cost of development and operation. The configuration of a hybrid motor resembles that of a solid rocket, as shown in Fig. 1, except that the solid propellant of the latter is replaced by solid fuel, and the oxidizer is injected through the central injector. Therefore, the reactant mixing during the hybrid combustion process is a serious problem when compared with solid rocket. The mixing in a hybrid motor always takes place at the surface of the melting or evaporating surface of the solid fuel. If the mixing is not well controlled, then much propellant may be left unburned, resulting in a low combustion efficiency.

Hybrid rocket burning is governed by complex mixing and vaporization processes. The flame develops with the oxidizer arriving from the spray injector and the fuel diffusing from the vaporizing solid boundary, as shown in Fig. 2. Vaporization of the solid fuel is primarily sustained by the rate of heat transfer to the surface by conduction, convection and radiation. Excess fuel not consumed in the upstream flame is carried downstream by the core flow and continues to react. Optimum design of a hybrid rocket booster requires a fundamental understanding of the flow and combustion processes. The capability to predict flow and combustion phenomenon within the solid grain port and through the

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Nomenclature

B	Spalding transfer number
B'	frequency factor
C_D	drag coefficient
C_p	heat capacity at constant pressure
C_s	stoichiometric ratio of oxygen mass to fuel mass
D	mass diffusion coefficient
E	activation energy
$\dot{G}$	total mass flux
h	total enthalpy, given by $\int_{298^o}^{T_g} C_p dT + Y_{ox} q^o / C_s$
H	effective droplet heat of vaporization
K	turbulent kinetic energy
L	latent heat
Le	Lewis number, given by $\lambda / \rho C_p D$
$\dot{m}$	evaporation/combustion rate
n_{d}	droplet number density
p	gas pressure
Pr	Prandtl number, given by $C_p \mu / \lambda$
q^0	heat of combustion
r	radial coordinate
$\dot{r}$	solid-fuel regression rate
r_d	droplet radius
$r_{d,l}$	droplet radius of lth group
r_{lm}	volume-mean droplet radius
r_∞	distance from droplet center to where ignition takes place
R_0	outlet radius of oxidizer injector
Re	Reynolds number
R_u	universal gas constant
T	temperature
u	axial velocity component
v	radial velocity component
$\mathbf{V}$	velocity vector
V_j	spray injection velocity
w	molecular weight
x	axial coordinate
Y	mass fraction

Greek symbol

α	spray cone angle also thermal diffusivity in Eq. (1)
ε	turbulent dissipation rate
θ	droplet void-deducted volume ratio
λ	heat conductivity
μ	dynamic viscosity
v	stoichiometric reactant coefficient
ρ	density

Subscript

0	inlet condition
b	boiling point
d	droplet
f	fuel
g	gas phase
l	lth size group of droplets
ox	oxidizer
pr	product
s	solid-fuel surface
t	turbulence
∞	infinity

nozzle at any design operating condition is of particular interest.

Since the fuel burning rate and oxidizer fraction consumed in a hybrid motor are functions of the flow conditions inside the engine, the design procedures are much more complex than those for solid or liquid rockets. Various researchers have attempted to establish the correlations between the fuel regression rate and the flow-rate parameters. Marxman [1,2] proposed an elaborate theory on the following assumptions: (1) diffusion is the dominant process; (2) the Reynolds analogy holds in the boundary layer outside the flame; (3) combustion occurs when the stoichiometric ratio is reached, and (4) the Lewis and Prandtl numbers are unity. They found that the fuel regression rate is proportional to the total mass flux raised to the power 0.8 ($\dot{r} \propto \dot{G}^{0.8}$). Many early researchers reported this finding, especially for those with inlet conditions of a fully developed turbulent boundary-layer flowfield [3–5]. Their correlations were then modified by Paul et al. [5], who emphasized the importance of the mass transfer number and block effect (reduction in skin friction coefficient with wall injection). However, recent works have often found that the power of the mass flux was too high, because the Marxman law was developed under a fuel slab configuration, whereas a practical hybrid rocket adopts a cylindrical configuration [6]. Moreover, many factors, including oxidizer-to-fuel ratio (*O*/*F* ratio), chamber configuration, chamber pressure, oxidizer injector design, fuel composition, curing process and scale effect, all significantly influence the regression data. Therefore, correlations that address many parameters have been developed [6,7].