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Numerical simulations on unsteady operation processes of N_2O/HTPB hybrid rocket motor with/without diaphragm

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ABSTRACT

Numerical simulations on processes within a hybrid rocket motor were conducted in the past, where most of these simulations carried out majorly focused on steady state analysis. Solid fuel regression rate strongly depends on complicated physicochemical processes and internal fluid dynamic behavior within the rocket motor, which changes with both space and time during its operation, and are therefore more unsteady in characteristics. Numerical simulations on the unsteady operational processes of N_2O/HTPB hybrid rocket motor with and without diaphragm are conducted within this research paper. A numerical model is established based on two dimensional axisymmetric unsteady Navier–Stokes equations having turbulence, combustion and coupled gas/solid phase formulations. Discrete phase model is used to simulate injection and vaporization of the liquid oxidizer. A dynamic mesh technique is applied to the non-uniform regression of fuel grain, while results of unsteady flow field, variation of regression rate distribution with time, regression process of burning surface and internal ballistics are all obtained. Due to presence of eddy flow, the diaphragm increases regression rate further downstream. Peak regression rates are observed close to flow reattachment regions, while these peak values decrease gradually, and peak position shift further downstream with time advancement. Motor performance is analyzed accordingly, and it is noticed that the case with diaphragm included results in combustion efficiency and specific impulse efficiency increase of roughly 10%, and ground thrust increase of 17.8%.

1. Introduction

Hybrid rocket motor (HRM) within the chemical propulsion family adopts a two-phase propellant system, where an oxidizer maintains a liquid phase and fuel is in a solid phase. Compared with traditional solid or liquid rocket motor, HRM possesses intrinsic properties such as simplicity, safety, reliability, low costs, throttling capabilities, etc., consequently projecting it as a prospective propulsion system [1–3]. The successful launch of HRM powered sub-orbital spacecrafts SpaceShipOne (SS1) and SpaceShipTwo (SS2) attracted wide attention from researchers and developers around the world, which further accelerated advanced development of HRM [4,5].

A classical HRM adopts straight-through structure with a single straight cylindrical port fuel grain. The liquid oxidizer is injected at the head-end of the combustion chamber. After atomization and vaporization occurs, the oxidizer reacts with gas fuel from the pyrolysis of solid fuel, thereby forming a boundary layer diffusion flame over the solid fuel surface. Through convective and radiative heat transfer, high temperature flames provide energy for vaporization of liquid oxidizer and pyrolysis of solid fuel, which further sustains the combustion process. A number of complex physical and chemical phenomena exist within the operational processes of HRM. The solid fuel regression rate, which represents the most important design parameter for HRM [6], is strongly dependent on these physicochemical processes and also on its internal fluid dynamic behavior. Within the fuel grain's burning surface, the oxidizer-to-fuel (O/F) ratio, heat and mass transfer, all vary with positions, thereby enabling the regression rate to vary axially. As the fuel regresses with time, the area of the port section becomes larger and the oxidizer mass flux is decreased, which influences the regression rate. Generally, the regression rate of HRM changes with both space and time during operation. However, it is difficult to obtain a regression rate expression suitable for different working conditions, which makes the regression rate computation a key factor of interest for HRM [7].

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Nomenclature

Variables

A	Arrhenius pre-exponential constant area
a	regression rate leading coefficient
c	specific heat capacity
d	diameter
E	activation energy
e	energy
G	mass flux
h	sensible enthalpy
J	diffusion flux
k	turbulence kinetic energy
M	molecular weight
m	mass
$\dot{m}$	mass flow rate
n	mass flux exponent
p	pressure
q	heat flux
R	universal gas constant
$\dot{r}$	fuel regression rate
S	source
T	temperature
t	time
v	velocity
Y	mass fraction
ε	turbulence dissipation rate
λ	thermal conductivity
μ	viscosity
ρ	density
τ	viscous stress
ω	net rate of production of species
ν'	stoichiometric coefficient for reactant
ν''	stoichiometric coefficient for product

Subscripts

a	atmosphere
ave	average
b	backward
d	droplet
e	exit of nozzle
eff	effective
f	forward
g	gas phase
n	normal direction
o	oxidizer
P	product species
p	pressure
R	reactant species
r	radial direction
re	reaction
ref	reference
s	solid phase
$surf$	surface
t	turbulence
x	axial direction
∞	continuous phase

Numerical simulation highlights an effective method of investigating the operation and progress within the HRM, where studies focused on analyzing the flow fields and regression rate distributions could be carried out, which consequently assists the design stages of HRM. In order to obtain reasonable and accurate regression rate distributions from numerical simulations, models to describe and capture interactions between the reacting flow and solid surface are required, and efforts have been carried out to identify such models. Cheng et al. [8] developed a numerical model for liquid oxygen (LOX)/ hydroxyl terminated polybutadiene (HTPB) HRM, which was based on a Navier-Stokes solver, the Finite Difference Navier-Stokes (FDNS) code. Fuel blowing rate was calculated by balancing the convective and radiative heating on the wall against heat of HTPB pyrolysis, coupling gaseous flow field with pyrolysis of HTPB. Venkateswaran and Merkle [9] coupled two-dimensional RANS equations with an Arrhenius-type semi-empirical regression rate equation experimentally obtained by Chiaverini et al. [10], thereby developing a numerical model for gaseous oxygen (GOX)/HTPB HRM. The calculated regression rate distributions matched well with experimental results. Based on this type of semi-empirical regression rate equations, researchers from Beihang University [11–18] developed a numerical model from 2D to 3D and applied it to tube grain, multi-port grain, star grain, wagon wheel grain and segmented grain. Simulation data acquired so far have been helpful in analyzing experimental results. Zhang et al. [19] applied their numerical model to a complex star swirl fuel HRM. Researchers from University of Padua [20–27] also represents such applications and advances in this direction. However, research progress and findings so far mentioned were duly focused on steady operational process of HRM, which takes no consideration of regression processes of the fuel grain. Regression rate changes with space but not with time in these mentioned works. Within the unsteady operational process of HRM, regression of the fuel grain constitutes difficulty, thereby making this an uneasy task to simulate as clearly seen by few of such unsteady simulations. Antoniou and Akyuzlu [28] developed a two-dimensional unsteady model, where the computational domain was divided into two parts; solid fuel and gaseous oxidizer having a moving interface. The interface moves at the regression rate, with mesh transformation and stretching occurring instantaneously. They simulated the unsteady operational process for 0.12 s, which proved to be a good attempt. Yang et al. [7] made use of a dynamic mesh technique to simulate non-uniform regression of burning surface of the fuel grain in a GOX/HTPB HRM. They simulated 2 s of operational process, and obtained the regression process of the fuel grain. Unfortunately, details of the utilized mesh were not included in their report. Shan et al. [29] developed a dynamic interface method within a fixed structure mesh, and applied it towards solving this problem, with their results matching well with experimental data.

The main objective of this paper is to numerically investigate the unsteady operational process within a hybrid rocket motor. The utilized numerical model, including governing equations, turbulence model, discrete phase model, combustion model and coupled gas/solid phase formulations are all presented. Dynamic mesh technique is applied in order to simulate the non-uniform regression. In a bid to capture better influence of the physicochemical processes and internal fluid dynamic behaviors on the regression rate, a tube grain comprising a diaphragm is compared with the same grain without diaphragm. The combination of propellant utilized is liquid nitrous oxide (N_2O) and HTPB. Non-uniform regression processes, spatial and time varied regression rate distributions and internal ballistic curves are all obtained. Influence of the diaphragm on regression rate and combustion efficiency are presented and discussed based on simulation results.