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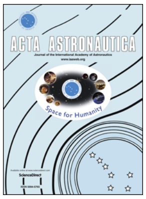

Heat and mass transfer analysis for paraffin/nitrous oxide burning rate in hybrid propulsion

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ABSTRACT

This research presents a physical-mathematical model for the combustion of liquefying fuels in hybrid combustors, accounting for blowing effect on the heat transfer. A particular attention is given to a paraffin/nitrous oxide hybrid system. The use of a paraffin fuel in hybrid propulsion has been considered because of its much higher regression rate enabling significantly higher thrust compared to that of common polymeric fuels. The model predicts the overall regression rate (melting rate) of the fuel and the different mechanisms involved, including evaporation, entrainment of droplets of molten material, and mass loss due to melt flow on the condensed fuel surface. Prediction of the thickness and velocity of the liquid (melt) layer formed at the surface during combustion was done as well. Applying the model for an oxidizer mass flux of 45 kg/(s m^2) as an example representing experimental range, it was found that 21% of the molten liquid undergoes evaporation, 30% enters the gas flow by the entrainment mechanism, and 49% reaches the end of the combustion chamber as a flowing liquid layer. When increasing the oxidizer mass flux in the port, the effect of entrainment increases while that of the flowing liquid layer along the surface shows a relatively lower contribution. Yet, the latter is predicted to have a significant contribution to the overall mass loss. In practical applications it may cause reduced combustion efficiency and should be taken into account in the motor design, e.g., by reinforcing the paraffin fuel with different additives. The model predictions have been compared to experimental results revealing good agreement.

1. Introduction

The application of hybrid propulsion has recently received attention for potential space missions. In particular, future space tourism vehicles are planned to use hybrid boosters. This era is indicated by the first private enterprise SpaceShip1 launched in 2004, see e.g., Ref. [1].

The common polymeric fuels in hybrid motors are characterized by low regression rate, hence yielding a relatively low thrust. Thus, liquefying fuels such as paraffin wax, which yield higher regression rates, have been studied. This research develops and analyzes a physical-mathematical model for the burning rate of paraffin/nitrous oxide in a hybrid system. The model follows the approach of Weinstein and Gany [2] for the combustion of liquefying fuels which aimed in particular to paraffin/oxygen propellant combination. A similar analysis was done previously by Gany and Caveny [3] for the case of metal erosion in high temperature flows that includes surface melting.

The present model aims at predicting the regression rate of a liquefying fuel in hybrid combustion, accounting for the contribution of three major mass loss mechanisms to the overall regression rate characterized by the fuel

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Nomenclature

d	port diameter [m]
G	mass flux [kg/m^{2}s]
h	convection coefficient [W/m^{2}K]
k	conduction coefficient [W/mK]
$\dot{m}$	mass flow rate [kg/s]
O/F	=oxidizer to fuel ratio [-]
P	pressure [atm]
q	heat flux [J/m^{2}s]
$\dot{r}$	regression rate [mm/s]
T	temperature [K]
u	velocity [m/s]

Greek

δ	thickness [mm]
μ	viscosity [poise]
ρ	density [kg/m^3]

Subscripts

a	ambient
c	combustion
cond	conduction
conv	convection
ent	entrainment
f	flame
g	gas
in	initial
l	liquid
m	melting
s	solid
ox	oxidizer
tot	total
v	vaporization

melting rate: Those are evaporation (or gasification), entrainment of liquid droplets from the surface melt layer to the gas stream, and the liquid layer flow along the surface of the solid fuel. The former two mass loss mechanisms in liquefying fuels were considered by Karabeyoglu et al. [4] and Karabeyoglu and Cantwell [5], whereas the latter (melt flow) was added by Weinstein and Gany [2]. In addition to these considerations, the present regression rate model includes the effect of blowing on the heat transfer from the hot gas to the surface, resulting from the flux of evaporating/gasifying fuel entering the boundary layer. It also accounts for the variation of physical properties as a function of temperature rather than using constant values. As the present research aims at characterizing and evaluating the specific surface phenomena that affect the fuel regression rate, it is not intended to solve the gas flow field, but rather use general approximations for heat transfer from the gas flow to the surface. The heat transfer through the narrow surface layer is assumed as one dimensional in the lateral direction. The model predictions have been compared to experimental results of Sisi [6] and Sisi and Gany [7] exhibiting good correlation.

2. Burning process of liquefying fuel

The burning process of a liquefying fuel occurs in a three-phase environment: solid, liquid, and gas. During the surface regression the following phenomena take place:

-The solid fuel reaches its melting temperature.

-A liquid layer forms on the fuel surface.

-The liquid layer flows along the fuel surface (as a result of shear forces from the gas flow).

-At the interface between the liquid layer and the surrounding hot gas, evaporation of the liquid fuel takes place.

Fig. 1 shows the zone where the liquid layer is formed as well as the heat transfer at the gas–liquid and liquid–solid interfaces. The melting and evaporation processes are due to heat transfer from the flame. Typically, in hybrid combustion diffusion flame between the fuel gases coming from the surface and the oxidizer gases from the core flow is established within the boundary layer adjacent to the condensed surface. Hence, chemical kinetics plays only a secondary role, and its effect is not considered here. The liquid layer is heated by forced convection from the hot boundary layer gas flow (radiation heat transfer is much smaller and was neglected in the calculation). Within the liquid layer and solid bulk heat is transferred by conduction. The fuel melting rate is considered as the overall regression rate of the fuel. As mentioned before, it is composed of three main mass loss mechanisms: evaporation, entrainment of droplets of molten material, and mass loss due to melt flow on the condensed fuel surface.

In steady state, the contributions of the different mechanisms to the regression rate are:

$$\dot{r} = \dot{r}_m = \dot{r} + \dot{r}_{ent} + \dot{r}_l \tag{1}$$

The thermal balance at the liquid layer, neglecting radiation, is:

$$q_{conv} = q_v + q_{cond,l \to s} \tag{2}$$

Thermal equation of the solid bulk:

$$q_{cond,l \to s} = q_m \tag{3}$$

The heat flux required for melting the solid q_m and the heat flux required for evaporating the liquid q_v are:

$$q_m = \rho_s \dot{r}_m h_m \tag{4}$$

$$q_v = \rho_l \dot{r}_v h_v \tag{5}$$

where the effective melting enthalpy h_m and the effective evaporation enthalpy h_v include the energy required for heating the fuel to the melting and evaporation temperatures, respectively, as well as the corresponding phase transition enthalpies.