Available online at www.sciencedirect.com
ScienceDirect
Energy Procedia 141 (2017) 267–272
Energy Procedia
www.elsevier.com/locate/procedia

4th International Conference on Power and Energy Systems Engineering, CPESE 2017, 25-29 September 2017, Berlin, Germany

Modeling of the Turbulent Combustion in Solid-fuel Ramjet

Lunkun Gong[a]*, Xiong Chen[a], Omer Musa[a]

[a]*Nanjing University of Science and Technology, Nanjing, 210094, People's Republic of China*

Abstract

An in-house multi-physics coupling code has been developed to solve the 3-D Navier-Stokes equations with chemical reaction to predict the unsteady turbulent combustion in solid-fuel ramjet. Firstly, the governing equations, chemical reaction models and numerical methods are illustrated in detail. Then the flow field of solid-fuel ramjet is analyzed. The results show that fuel-rich region exists near the fuel surface and oxygen-rich region exists near the central axis. Finally, the calculated regression rate is compared with those obtained with connected-pipe test. The good agreement demonstrates the predictive capability of the developed code.

Keywords: solid-fuel ramjet; multi-physics coupling code; regression rate; combustion characteristics

1. Introduction

Solid-fuel ramjet (SFRJ) is an attractive air-breathing propulsion system due to its simple structure. The schematic diagram of solid-fuel ramjet is shown in Fig. 1. The incoming air is compressed by an air intake system, then mixes and reacts with the solid fuel pyrolysis products in the recirculation zone behind the backward-facing step. Downstream of the reattachment point, the diffusion flame between the solid fuel pyrolysis products and the incoming air exists near the solid fuel surface. In the aft-chamber, the unreacted mixed gases will continue to react, which improves the ramjet combustion efficiency [1].

The combustion in SFRJ is diffusion-controlled, and many studies have been conducted to investigate the diffusion-controlled combustion characteristics aimed at improving engine performances. The effects of fuel

* Corresponding author. Tel.: 86-025-84315605; fax: 86-025-84315605
E-mail address: glunkun@163.com

1876-6102 © 2017 The Authors. Published by Elsevier Ltd.
Peer-review under responsibility of the scientific committee of the 4th International Conference on Power and Energy Systems Engineering.
10.1016/j.egypro.2017.11.104

components such as mental additives have been widely researched to increase the fuel regression rate [2-5]. Beside the conventional tubular solid fuel, different non-conventional configurations have been explored to improve engine performance [6, 7]. In the current theoretical investigations, beside the analysis based on traditional heat-transfer theory [1,8], Computational fluid dynamics (CFD) has been a useful tool in predicting the diffusion-controlled combustion, which allows experimental tests to be conducted only in the last period of real project, reducing research cost and shorten research cycle. In 1990s, Elands et al. [9] developed a computer code called COPPEF describing the flow and combustion process in solid-fuel ramjet, in which *k*-epsilon turbulence model was applied in combination with standard wall function. Finite-rate kinetics and diffusion flame model were implemented. In recent years, various in-house codes and commercial softwares are both wildly employed to model the diffusion-controlled combustion [10-12]. Due to the improvement of numerical methods and deeper understanding of the combustion process of solid fuel, the combustion modeling of diffusion-combustion in solid-fuel ramjet is always proceeding.

In order to predict the combustion process in SFRJ, an in-house multi-physics coupling code is developed by solving the Navier-Stokes governing equations coupled with continuity, energy and species transport equations in the present research. Then the combustion characteristics of solid-fuel ramjet are investigated with the present code, demonstrating the predictive capability of the developed code.

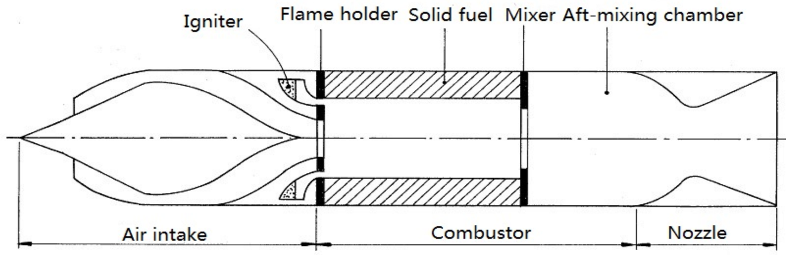

Fig. 1. Schematic diagram of solid-fuel ramjet.

2. Numerical method

2.1. Gas-phase governing equation

In the present investigation, three-dimensional equations are applied to model the combustion process in solid-fuel ramjet. The gas-phase governing equations are expressed in the following form:

$$\frac{\partial}{\partial t}\iiint_{\Omega}\boldsymbol{U}dV+\iint_{\partial\Omega}\boldsymbol{F}_c\cdot\boldsymbol{n}dS-\iint_{\partial\Omega}\boldsymbol{F}_v\cdot\boldsymbol{n}dS=\iiint_{\Omega}\boldsymbol{S}dV \tag{1}$$

Where U is conservative vector, F_c is convective flux vector, $\boldsymbol{F}_v$ is viscous flux vector, S is chemical reaction source term, in which the mass, momentum and energy source terms result from the fuel adding into the chamber near the solid fuel surface due to pyrolysis of the solid fuel. These vectors are given by

$$\boldsymbol{U}=\begin{bmatrix}\rho\\ \rho u\\ \rho v\\ \rho w\\ E\\ \rho_i\end{bmatrix}\quad \boldsymbol{F}_c=\begin{bmatrix}\rho u\boldsymbol{i}+\rho v\boldsymbol{j}+\rho w\boldsymbol{k}\\ (\rho u^2+p)\boldsymbol{i}+\rho uv\boldsymbol{j}+\rho uw\boldsymbol{k}\\ \rho uv\boldsymbol{i}+(\rho v^2+p)\boldsymbol{j}+\rho vw\boldsymbol{k}\\ \rho uw\boldsymbol{i}+\rho vw\boldsymbol{j}+(\rho w^2+p)\boldsymbol{k}\\ (E+p)u\boldsymbol{i}+(E+p)v\boldsymbol{j}+(E+p)w\boldsymbol{k}\\ \rho_i u\boldsymbol{i}+\rho_i v\boldsymbol{j}+\rho_i w\boldsymbol{k}\end{bmatrix}\quad \boldsymbol{F}_v=\begin{bmatrix}0\\ \tau_{xx}\boldsymbol{i}+\tau_{xy}\boldsymbol{j}+\tau_{xz}\boldsymbol{k}\\ \tau_{yx}\boldsymbol{i}+\tau_{yy}\boldsymbol{j}+\tau_{yz}\boldsymbol{k}\\ \tau_{zx}\boldsymbol{i}+\tau_{zy}\boldsymbol{j}+\tau_{zz}\boldsymbol{k}\\ \Pi_x\boldsymbol{i}+\Pi_y\boldsymbol{j}+\Pi_z\boldsymbol{k}\\ \rho D_i\frac{\partial c_i}{\partial x}\boldsymbol{i}+\rho D_i\frac{\partial c_i}{\partial y}\boldsymbol{j}+\rho D_i\frac{\partial c_i}{\partial z}\boldsymbol{k}\end{bmatrix}$$