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Effect of backward facing step on radiation efficiency in a micro combustor

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ABSTRACT

The present study investigates the effect of backward facing step in a micro combustor on blowout limit and outer wall temperature. Effect of equivalence ratio of hydrogen-air mixture and combustor material (i.e. conductive heat transfer coefficient) on emitter efficiency and radiation efficiency perused. In addition, the effect of step height and diameter of combustor are studied. The results show that the presence of backward facing step leads to increase blowout limit and mean wall temperature. Temperature distribution along external wall of micro combustor shows a uniform distribution. It is also observed that combustor with lower step height has higher (mean) wall temperature. Maximum mean wall temperature and radiation efficiency achieved when equivalence ratio is located in lean values. It has been also observed that the wall thermal conductivity has an optimum value to obtain maximum radiation efficiency.

1. Introduction

With growing of portable devices such as laptops and cellphones, using of a trustable power supply with high energy density is necessary. While Available lithium batteries have low energy density (about 0.2 kWh/kg), the energy density of hydrocarbon fuels is approximately 50 times more than usual lithium batteries [1]. One of the best methods for releasing the energy of hydrocarbon fuels is combustion process. Using of this power source in electronic devices need to develop microscale combustors.

In the recent decade, huge efforts have been devoted on this issue by different researchers. Pen et al. [1] used a micro combustor as a radiative emitter in the thermo photovoltaic micro generators. They investigated the effects of equivalence ratio of hydrogen-air mixture and wall thickness of micro combustor on radiation efficiency. According to their results, the maximum outer mean wall temperature for the hydrogen-air mixture achieved at lean mixture. In addition, they showed that a combustor with thinner wall thickness has higher mean temperature on the external wall. Vlachos [2] studied the effects of different parameters, such as convective heat transfer coefficient, thermal conductivity of combustor wall and inlet velocity on the flame location and wall temperature distribution. According to their numerical results, reducing the wall thermal conductivity causes a decrease in heat losses from combustor and the flame forms farther then inlet boundary. This is because of decrease in the preheating role of the walls on inlet mixture. They also mentioned that increasing of wall thermal conductivity until a specified value, causes the flame move towards combustor inlet, and after that, flame location moves towards the downstream due to increasing of heat losses. Using backward facing step and bluff body in micro combustor can be a suitable solution to control the flame location. Yang et al. [3] compared the combustion characteristics in a micro-cylindrical combustor with and without backward facing step. They announced that using backward facing step leads to an uniform temperature distribution in the external wall due to increases of residence time of the mixture in the combustor. In addition, they showed that using backward facing step in the combustor provides a complete combustion. Baigmohammadi et al. [4] investigated numerically the behavior of methane-hydrogen/air pre-mixed flame in a micro combustor equipped with catalytic segment. Their results showed that using catalytic segment with high thermal conductivity especially in high inlet velocity could increase blow out limit. Baigmohammadi et al. [5] conducted a numerical investigation on the effect of adding hydrogen into methane – air mixture in a micro step tube. Their study showed that adding hydrogen to methane - air mixture could improve the flame presence in micro combustor. Baigmohammadi et al. [6] also investigated the effects of inserting the wire in a micro combustor. Using wire in micro combustor leads to a higher flame stability in high velocities. Li et al. [7] studied experimentally the effect of geometric parameters such as combustor diameter, step height and physical parameters of the fuel-air mixture (i.e. equivalence ratio and inlet velocity). Based on their research, equivalence ratio intervals from 0.6 to 0.9 causes a significant increase in external wall temperature. Upon increase of equivalence ratio to 1.0, variation of mean wall temperature is approximately negligible. In addition, they reported that increasing

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Nomenclature

D_{im}	average diffusivity of the ith species (m2/s)
R_u	universal gas constant(J/kmol-K)
D_{ij}	binary diffusion coefficient of the ith species in jth species (m2/s)
T	temperature (K)
hh	enthalpy (J/kg)
u	velocity vector (m/s)
$\dot{m}_{H2}$	mass flow rate of the fuel
$\overline{W}$	mean molecular weight of the mixture
P	pressure (Pa)
X_i	mole fraction of specie i
$\dot{Q}_{wa}$	heat transfer rate from the external walls
Y_i	mass fraction of the ith species
$\dot{Q}_R$	chemical heat release rate
$\dot{Q}_{rad}$	radiation heat transfer rate
$\dot{Q}_{LHV}$	lower heating value of hydrogen fuel

Greek symbols

ρ	density (kg/m3)
Ω_D	collision integral
μ	dynamic viscosity
η_q	energy conversion efficiency
λ	thermal diffusivity
η_{rad}	emitter efficiency
ϕ	equivalence ratio
η_{total}	total energy conversion efficiency of the TPV
σ_i	collision diameter (A)
σ	Boltzmann constant
ε_α	Lennard-Jones energy
ε	surface emissivity
$\dot{w}_i$	rate of reaction of the ith species

Subscripts

f	fluid
ij	i^{th} species in jth species
wall	wall
im	i^{th} species in the mixture
in	inlet
s	surface
i	i^{th} species
sur	surrounding

the combustor diameter and step height has a significant effect on the combustor characteristics such as external wall temperature and blow-off limit.

Chou et al. [8] made a numerical investigation on the effects of using porous media in the thermos-photovoltaic generator efficiency. They showed that using porous media causes to increase of temperature along the micro combustor wall and creates a more uniform temperature distribution on the external wall. Wan et al. [9] investigated combustion characteristics in a micro combustor with a bluff body. Their results showed that the blow-off limit is greatly extended in the presence of the bluff body.

In the last two decades, many experimental [10,11] and numerical [12–14] research have been done for combustion phenomenon in micro scale. The most of them suggested that increasing of residence time and mixing parameter could increase flame stability in micro combustion. One of suggested methods is using the bluff body in micro combustor that can create a heat vortex in micro combustor and consequently increase flammability of the flame. Also, since 2005 up to now many experimental and numerical works such as [15–20] investigated various flame regime and their reasons.

Based on the reviewed literature, for increasing the flammability of the flame in micro combustor, it is needed to create a heat vortex in micro combustor based on excess enthalpy approach. In the present research, the effects of presence of backward facing step in a micro combustor is investigated numerically on combustion characteristics of hydrogen-air mixture. Frist, the effect of presence of backward facing step in a channel is composed with a combustor without the backward facing step. Then, the effect of geometry parameters such as height of step and diameter of the channel is investigated on flame location and maximum temperature of the flow. In continue the effect of equivalence ratio and wall thermal conductivity of the combustor is studied on radiation efficiency in a micro combustor with backward facing step. And finally, the effect of wall thermal conductivity is discussed on flame location and temperature distribution And radiation efficiency.

2. Governing equations

Governing equations include the continuity, momentum, energy, species conservation equations and the ideal gas equation of state in the fluid, which are given by Eqs. (1)–(5), respectively, and energy equation in the solid wall given by Eq. (6) which are numerically solved by the finite volume solver.

2.1. Continuity

$$\frac{\partial(\rho u_i)}{\partial x_i}=0 \tag{1}$$

Momentum:

$$\frac{\partial(\rho u_i u_i)}{\partial x_i} = -\frac{\partial(p)}{\partial x_i} + \frac{\partial}{\partial x_i}\left(-\frac{2}{3}\mu\frac{\partial u_k}{\partial x_k}\delta_{ij} + \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right) \tag{2}$$

Where ρ, u and μ are density, velocity vector, and dynamic viscosity, respectively.

2.2. Energy in the fluid

$$\frac{\partial(\rho u_i h)}{\partial x_i} = -\frac{\partial}{\partial x_i}\left(\lambda_f\frac{\partial T}{\partial x_i}\right) + \frac{\partial}{\partial x_i}\left(\rho\sum_{k=1}^{N} h_k y_k v_{k.i}\right) + \dot{w} \tag{3}$$

Where λ_f and h_i are mixture thermal diffusivity and enthalpy for the ith species, respectively.

2.3. Species conservation equation

$$\frac{\partial(\rho u_i y_i)}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\rho D_{i.m}\frac{\partial y_i}{\partial x_i}\right) + \dot{w} \tag{4}$$

y_i and $\dot{w}_i$ are the mass fraction of species and rate of reaction of the ith species. Density is also calculated from the ideal gas equation of state that is written as:

$$p = \rho\frac{R_u}{\overline{W}}T \tag{5}$$

Where $\overline{w}$ is the mean of molecular weight of the mixture and R_u is the universal gas constant.