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Research Paper

Investigation on the combustion performance enhancement of the premixed methane/air in a two-step micro combustor

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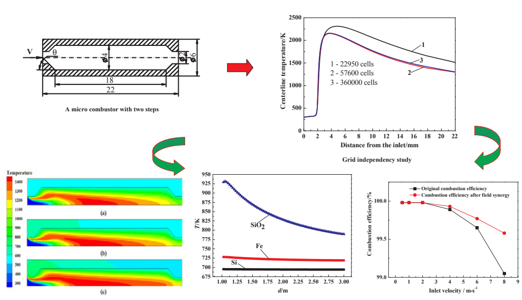
HIGHLIGHTS

- A two-step global reaction mechanism is used to study the chemical reactions.
- Methane combustion model of a two-step micro combustor is established.
- Effects of the some kinds of premixed methane combustion are investigated.
- Field synergetic theory is used to analyze the premixed methane/air combustion.

GRAPHICAL ABSTRACT



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ABSTRACT

After a two-step global reaction mechanism is used to compute the chemical reactions of the reacting flows, a premixed methane/air combustion model of a two-step micro combustor is established based on some effect factors such as step angle, wall materials and inlet velocity. Moreover, the three or four kinds of the micro two-step combustors are used to investigate the effect of flame shape in the micro-channel, temperature characteristic, velocity field on the premixed methane combustion and field synergetic degree of the premixed methane/air combustion. It's shown that a suitable step angle and inlet velocity are very useful for enhancing the stability of methane premixed combustion of the two-step micro combustor, and the methane premixed combustion of the two-step micro combustor is also influenced by the wall matericals. Average temperatures of the outlet and combustion efficiencies of the two-step micro combustor at different inlet velocities are verified by the measurement results. It's shown that there are good comprehensive performance and higher synergy degree of the two-step micro combustor at the inlet velocities of 2 m/s and 4 m/s, and there are more and more obvious differences between combustion efficiency after field synergy and original combustion efficiency when the inlet velocities are increased.

1. Introduction

With the development of computer technology & microelectronic and the increase of energy demand [1–3], the research on Micro Power Generation Systems (MPGS) of high energy density had become a hot topic for many scholars [4–8]. Considering that micro combustor was a core component of micro power generation systems, it was urgent to study its combustion mechanism and structure model [9–14].

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Nomenclature

A_f	area of fluid computational domain in the two-step micro combustor, m^2
A_t	area of the grid element t whose synergy angle cosine is greater than or equal to 0.8, m^2
c_p	specific heat capacity, J/(kg K)
$D_{i,m}$	molecular diffusion coefficient of the component i of the mixture m
h	total enthalpy of the fluid, J
h_i	enthalpy of component i, J
k_i	thermal conductivity of the fluid, W/(m^2 K)
p	fluid pressure, Pa
R_i	generating or consumption rate of the component i, m/s
T	fluid temperature, K
$\vec{u}$	velocity vector, m/s
ν_x	speed component in the direction of x, m/s
ν_y	speed component in the direction of y, m/s
Y_{in}	volume fraction at the inlet of the two-step micro combustor
Y_j	volume fraction of component j
Y_{out}	average volume fraction of unburned fuel at the outlet of the two-step micro combustor
ρ	fluid density, kg/m^3
τ_{xy}	viscous shear stress of molecular, Pa
λ_f	thermal conductivity of fluid [W/(m K)]
∇T	temperature gradient, K/m
φ	synergy angle between velocity vector $\vec{u}$ and temperature gradient ∇T
$\partial T/\partial x$	axial temperature gradient, K/m
$\partial T/\partial r$	radial temperature gradient, K/m

Therefore, the research of micro scale combustion was of great significance [15–17].

Some researches on micro gas turbine and micro engine had been carried out. For example, startup methods, inlet temperature and pressure of the externally fired micro gas turbine with small scale were experimentally studied by Al-attab et al. [18]. The biogas was used to drive micro gas turbine cogeneration systems and the results were compared with existing operational data [19]. The efficiency and feasibility of the trigeneration system had been investigated experimentally [20]. The performance of a micro engine driven by heptane was studied by Wang et al. [21]. The potential benefits of the combined micro-turbine organic Rankine cycle were analyzed from the view of economic perspective, energetic perspective and environmental perspective [22].

Moreover, other researches on micro-combustor and cylindrical micro-combustors were reported. For example, in order to improve the energy conversion efficiency, lots of methods had been investigated and tested [23,24]. Heat recirculating was taken as an efficient method. The Swiss-roll combustor as the recirculated combustor was investigated by Gupta, Shirsat, Wierzbicki and Ahn et al. [25–29], it was shown that the reaction heat of the flow recirculation in the combustion zone was transferred to the incoming unburned and cold reactants through the combustor wall, serving as an ignition source. The combustion efficiency of micro-combustor was enhanced by premixed gas which was presented by Spadaccini et al. [30]. The flame propagation of a micro-combustor near extinction condition was numerically studied and the correlative experiments had been used to test the simulation results [31]. The thermal performance of micro-combustors with baffles and its entropy generation of H_2/air premixed flame were analyzed by Jiang et al. and Yang et al. [32–36]. The effects of backward facing step on combustion of two kinds of micro-cylindrical combustors were analyzed, and it's shown that the backward facing step was useful for enhancing combustion performance of micro-cylindrical combustors [37]. A method for improving the output power of micro-combustion chamber based on transient flame characteristics and wall heat flow was presented in Li et al. [38–41]. The heat transfer of cylindrical micro-combustion chamber was studied by means of one-dimensional cylinder micro-combustion chamber model. The combustion characteristics of hydrogen and oxygen premixed combustion in micro-porous medium combustor were studied; The effect of heterogeneous reaction products on the homogeneous combustion of H_2/O_2 mixture and the effect of hydrogen mixing mode on the combustion process of natural gas/hydrogen mixed fuel rotary engine were analyzed which were served as the a reference for the design of micro cylindrical combustor [42–44]. Through a piecewise polynomial fitting of temperature, the mixture gas thermal conductivity and viscosity and the specific heat of each component were calculated, some meaningful conclusions on combustion characteristics and performance evaluation of premixed methane/air with hydrogen were obtained [45,46]. The effect of thermal conductivity of solid wall on combustion efficiency of a micro-combustor with cavities and effect of external surface emissivity on flame-splitting limit in a micro cavity-combustor were investigated, some meaningful conclusions on combustion efficiency of a micro-combustor with cavities were obtained [47,48].

In the above studies, the analysis on the stability enhancement of the premixed methane/air combustion in a two-step micro combustor had rarely been studied [49–55]. Therefore, in order to investigate the effect factors of methane combustion in a two-step micro combustor, a premixed methane/air combustion model of micro combustor is established by CFD software FLUENT and combustion process of premixed methane/air by using of two-step reactions will be simulated and the effects of flame shape in the micro-channel, temperature characteristic and velocity field on the combustion of premixed methane will be investigated by numerical simulations and experimental verification.

In this paper, the stability of premixed methane/air combustion in two-stage micro-combustor is analyzed by using the field synergy principle, and the stability of premixed methane/air combustion in two-stage micro-combustor is improved.

2. Numerical methods

In this paper, the flow field in a micro combustor with different wall materials and inlet velocities is numerically simulated by CFD software FLUENT. Some assumption can be expressed as follows: (1) the methane-air mixture is fully mixed before entering the micro combustor, (2) the heat transfer and flow conditions on the outer surface of micro combustor wall are uniform. Therefore, the physical model of the two-step micro combustor can be simplified into a two-dimensional axisymmetric calculation model. Standard k-ε turbulence model is selected. A two-step global reaction mechanism is used to compute the chemical reactions of the reacting flows. In the two-step total package reaction model, the eddy dissipation model is used. Calculation is based on the standard pressure solver SIMPLE algorithm, and second order upwind difference scheme is chosen for equations of momentum and species. The relaxation factor of the momentum equation is 0.7, the relaxation factors of energy and species equations are both 1.0. The residuals of the momentum equation, continuity equation and the component equation are set to 1×10^{-3}, and residual of energy equation is 1×10^{-6}.

2.1. Combustor configuration

As shown in Fig. 1, outer diameter of the two-step micro combustor