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Numerical Study of the Flame Geometric Characteristics of Methane-Hydrogen-Air Combustion

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Abstract

This paper uses a two-dimensional axisymmetric simulation method to numerically simulate the combustion of hydrogenated methane mixtures. The numerical calculations are based on the RNG turbulence k-ε model and the ED combustion model, studying the flame geometric characteristics and temperature characteristics of hydrogenated methane. The combustion characteristics, flame structure, and regularity under different hydrogen mixing ratios are obtained. The results show that with the increase in hydrogen blending ratio in methane, the size of the high-temperature zone began increases and then decreases, while the highest temperature remains relatively stable. The flame length does not show significant changes with the increase in hydrogen blending ratio. With the increase in fuel flow rate, the size of the high-temperature zone increases, the highest temperature increases, and the flame is delayed.

Keywords

Methan; Hydrogen blending ratio; Combustion; Eddy dissipation.

1. INTRODUCTION

According to recent studies [1, 2], methane is the main component of natural gas, and researchers have conducted experimental and numerical investigations on the combustion characteristics of methane-hydrogen blends. It has been found that with an increase in the hydrogen blending ratio, the adiabatic flame temperature keeps rising. Numerical studies by Xu et al [3]. have shown that with an increase in the hydrogen blending ratio, the flame front moves forward, the maximum temperature of the flame increases, and the combustion characteristics of hydrocarbon fuels can be improved, achieving stable combustion. Wang's research [4] revealed that when the hydrogen concentration increases, the proportions of the three intermediate radicals H, O, and OH increase while the methane intermediate products decrease, indicating a shift towards low-carbon oxidation of methane. Yan's study [5] on catalytic combustion of methane-hydrogen blends demonstrated that the addition of hydrogen can reduce ignition time and improve combustion stability. In addition, studies have also been conducted on the ignition characteristics [6, 7] and emission characteristics of methane-hydrogen blends [8], as well as the feasibility of blending hydrogen into the urban natural gas pipeline network [9, 10]. The literature [11] has also investigated the flame geometric characteristics during methane-air turbulent combustion with different ratios of hydrogen, showing that the addition of hydrogen leads to reactions occurring in a lower temperature region, thereby improving the combustion efficiency of methane-air flames.

The gas burner is a crucial component of gas boilers, determining the ignition and combustion state of the fuel, and its operation characteristics are essential for the boiler's economy and reliability. In the design process, selecting and calculating the burner type is a key

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step. The length and diameter of the flame are important parameters in industrial boiler design and serve as the basis for design. This paper adopts numerical calculation methods to study the flame geometric characteristics of methane-hydrogen mixed fuels on industrial boiler burners, providing reference and basis for the design and retrofitting of burners in new energy industrial boilers.

2. MATHEMATICAL MODEL AND NUMERICAL METHODS

2.1. computation domain and mesh

This article utilizes a burner shown in Figure 1. Considering the symmetry of the burner chamber, the computational domain is simplified into a two-dimensional axial symmetry model. The overall dimensions of the burner are a length of 3000mm and an inner diameter of 500mm. The two-dimensional mesh is made up of 57700 elements, this mesh criterion was taken from Ref.[12]. The computational model is illustrated in Figure 1.

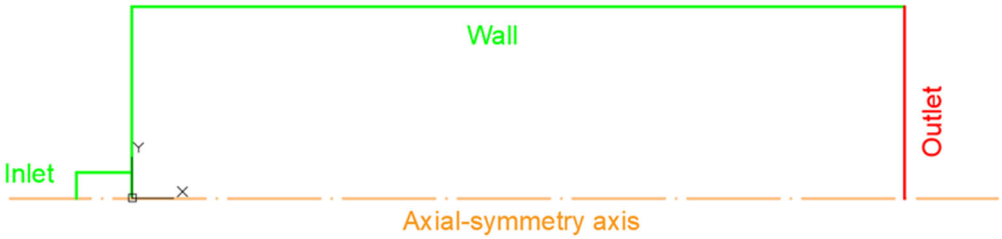

Figure 1. Schematic of the burner chamber

2.2. Theoretical background

Numerical calculations of combustion require fundamental control equations, including the continuity equation, momentum conservation equation, energy conservation equation, and chemical species transport equation. In this study, for the combustion in a gas boiler, the Navier-Stokes (N-S) equations are employed to describe fluid flow, the RNG k-epsilon (k-e) equations are utilized as the turbulence model, and the ED (Eddy dissipation) model is adopted as the combustion model[13]. The SIMPLE algorithm is used as the pressure-velocity coupling method.

The numerical simulation of combustion uses a one-step reaction mechanism, while assuming complete combustion of the fuel into CO_2 and H_2O.

The reaction equation is:

$$CH4+2O2->CO2+2H2O \quad (1)$$

$$H2+0.5O2->H2O \quad (2)$$

The continuity equation is written in the following form:

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u_i)}{\partial x_i}=0 \quad (3)$$

where， ρ is density， u_i are velocity components.

The momentum equations are written:

$$\frac{\partial(\rho u_i)}{\partial t}+\frac{\partial(\rho u_i u_j)}{\partial x_i}=\frac{\partial}{\partial x_i}[\mu\frac{\partial u_i}{\partial x_i}-\rho\overline{u'_i u'_j}]-\frac{\partial p}{\partial x_i}+S_i \quad (4)$$

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Where,μ is Dynamic viscosity，$\overline{u'_\iota}$ are fluctuating velocity components，p is pressure,S_i are source terms.

The energy equation is written:

$$\frac{\partial(\rho h)}{\partial t}+\frac{\partial(\rho u_j h-F_{h,j})}{\partial x_j}=\frac{\partial p}{\partial t}+\frac{\partial(\overline{u_j}p)}{\partial x_j}-p\frac{\partial u_j}{\partial x_j}+\tau_{ij}\frac{\partial u_i}{\partial x_j}+S_i \tag{5}$$

For gas combustion, the thermodynamic equation of state is defined as follows:

$$\rho=\rho(p,T) \tag{6}$$

Turbulence models

This study focuses on the combustion of gas boilers, where the gas flow inside the furnace is turbulent flow. RNG k- ε turbulence model commonly used in combustion calculations, these models consist of two equations: turbulent kinetic energy equation and dissipation rate equation. The equations expression is as follows:

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho k u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k+G_b-\rho\epsilon-Y_M+S_k \tag{7}$$

$$\frac{\partial(\rho\epsilon)}{\partial t}+\frac{\partial(\rho\epsilon u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\epsilon}\right)\frac{\partial\epsilon}{\partial x_j}\right]+C_{1\epsilon}\frac{\epsilon}{k}(G_k+C_{3\varepsilon}G_b)-C_{2\varepsilon}\rho\frac{\epsilon^2}{k}+S_\epsilon \tag{8}$$

In above equations ,$G_k$represents the generation of turbulence kinetic energy due to the mean velocity gradients, G_b is the generation of turbulence kinetic energy due to buoyancy,

Y_m represents the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate and $S_k, S_\varepsilon$are user-defined source terms. $C_{1\epsilon}$, $C_{2\epsilon}$, $C_{3\epsilon}$and σ_k , σ_ϵ are constants.

The species transport equations are written:

$$\frac{\partial(\rho Y_i)}{\partial t}+\frac{\partial(\rho u_j Y_i-J_i)}{\partial x_j}=R_i+S_i \tag{9}$$

Where, where R_i is the net rate of production of species by chemical reaction and S_i is the rate of creation by addition from the dispersed phase plus any user-defined sources. J_i is the diffusion flux of species i .

The Eddy-Dissipation Model

Under some combustion conditions, fuels burn quickly and the overall rate of reaction is controlled by turbulent mixing. the eddy-dissipation model, the net rate of production of species is given by the smaller (that is, limiting value) of the two expressions below:

$$R_{i,r}=v'_{i,r}M_{w,i}A\rho\frac{\varepsilon}{k}\min_R\left(\frac{Y_R}{v'_{R,r}M_{w,R}}\right) \tag{10}$$

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$$R_{i,r} = v'_{i,r} M_{w,i} AB\rho \frac{\varepsilon}{k} \frac{\sum_p Y_p}{\sum_j^N v''_{j,r} M_{w,j}} \quad (11)$$

where,Y_p is the mass fraction of any product species p,Y_R is the mass fraction of a particular reactant R, A is an empirical constant equal to 4.0. B is an empirical constant equal to 0.5.

Radiation Model

Under high temperature conditions, gas boilers must consider radiation and choose the DO radiation model in numerical calculations.

2.3. Boundary and initial conditions

Flow rate and mass flow inlet conditions are selected for air inlet, swirling speed also be considered for air flow， Turbulent intensity is set to 10%. Under different working conditions, the molar ratio of hydrogen in the fuel is shown in Table 1.

Fuel inlet are set to velocity inlet conditions, Turbulent intensity is set to 10%， The exit boundary condition is set as pressure outlet， Turbulent intensity is set to 2%[4, 14].

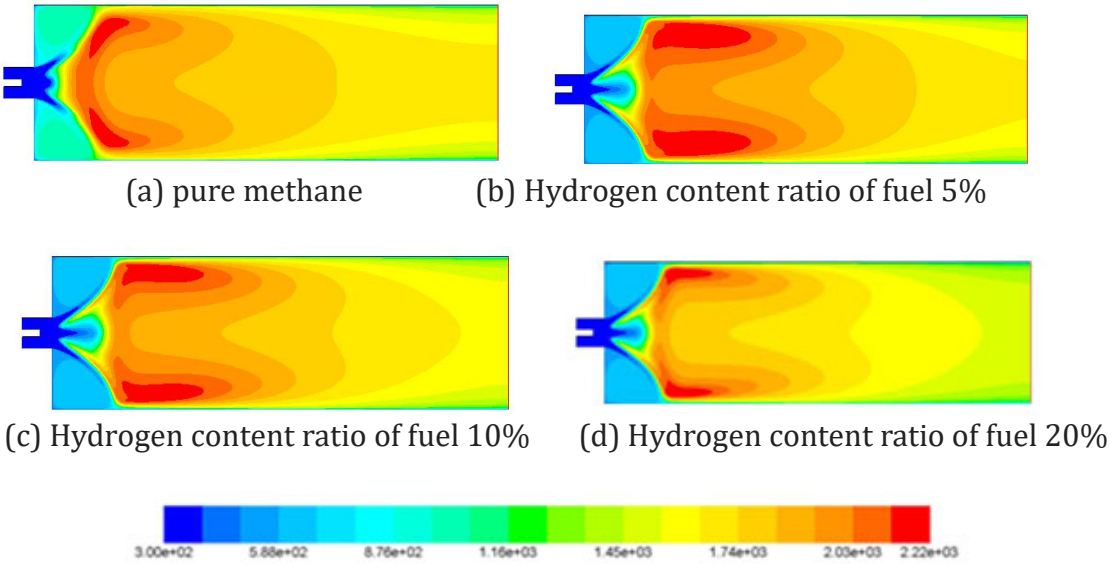
The circumferential wall is set as a constant temperature boundary, and other walls are set as adiabatic boundary.

Table 1. Molar fuel composition of fuel flow

Index	mixture composition
1	5%H_2+95%CH_4
2	10%H_2+90%CH_4
3	15%H_2+85%CH_4
4	20%H_2+80%CH_4

3. RESULTS AND DISCUSSION

In this paper, the numerical method is used to simulate the flame structure of mixed hydrogen in methane combustion. Figure 2 and Figure 3 are the temperature contours.



(a) pure methane (b) Hydrogen content ratio of fuel 5%

(c) Hydrogen content ratio of fuel 10% (d) Hydrogen content ratio of fuel 20%

Figure 2. Temperature(K) distribution of methane at different hydrogen ratios

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From Figure 2, we can see the comparison of burner temperature field under different hydrogen ratios, As the ratio of hydrogen mixed into methane increases, the size of the high-temperature region initially becomes larger and then smaller, with little change in the highest temperature fields. The flame front moves forward. With an increase in the hydrogen blending ratio, combustion occurs earlier, and the flame front moves forward.

From Figure 3, we can see that, as the flow rate increases the size of the high-temperature region expands, and the highest temperature increases. The flame delays, and the highest temperature of the flame increases with the increase in the hydrogen blending ratio.

It can be observed that the flame length does not show significant changes with an increase in the mole ratio of hydrogen. However, the high-temperature region of the flame increases, which is consistent with the experimental results reported in reference[15]. Particularly, as the mole ratio of hydrogen increases, the entire high-temperature region gradually moves forward.

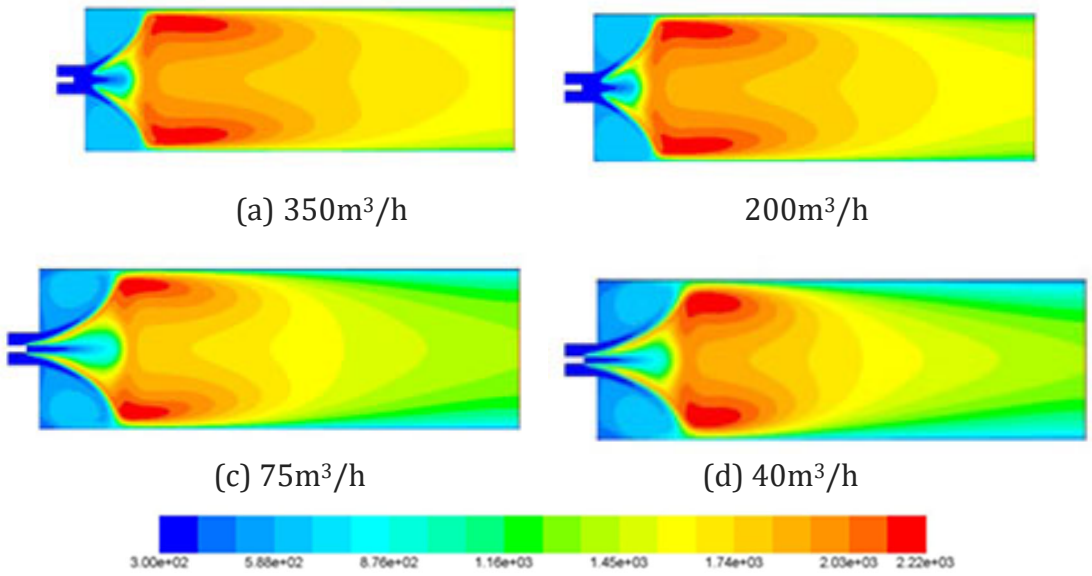

Figure 3. Temperature(K) distribution at different fuel flows rate at 10% hydrogen in fuel

4. CONCLUSIONS AND PERSPECTIVES

This article conducts numerical simulations of methane-hydrogen combustion using the RNG k-ε model and the ED combustion model, employing the Simple algorithm. The following conclusions are drawn:

(1) Hydrogen exhibits a higher flame propagation speed, lower highest temperature, and primarily produces water as its main product. It possesses significant environmental advantages. By gaining an in-depth understanding of the characteristics of methane-hydrogen combustion, support is provided for optimizing combustion processes and improving energy utilization efficiency.

(2) With an increase in the hydrogen blending ratio, combustion occurs earlier, and the flame front moves forward. As the hydrogen blending ratio increases, the size of the high-temperature region initially expands and then contracts, with little change in the highest temperature.

(3) The flame length does not show significant changes with an increase in the hydrogen blending ratio. However, as the flow rate increases, the size of the high-temperature region expands, leading to an increase in the highest temperature and a delay in the flame.

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