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Combustion characteristics of low concentration coal mine methane in divergent porous media burner

Lin Baiquan, Dai Huaming *, Wang Chaoqun, Li Qingzhao, Wang Ke, Zheng Yuanzhen

School of Safety Engineering, China University of Mining & Technology, Xuzhou 221116, China
State Key Laboratory of Coal Resources and Safe Mining, Xuzhou 221116, China

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ABSTRACT

Low-concentration methane (LCM) has been one of the biggest difficulties in using coal mine methane. And previous studies found that premixed combustion in porous media is an effective method of low calorific gas utilization. This paper studied the combustion of LCM in a divergent porous medium burner (DPMB) by using computational fluid dynamics (CFD), and investigated the effect of gas initial temperature on combustion characteristic, the distribution of temperature and pollutant at different equivalence ratios in detail. Besides, the comparison of divergent and cylindrical burners was also performed in this paper. The results show that: the peak temperature in DPMB increases as the increasing of equivalence ratio, which is also suitable for the outlet NO discharge; the linear correlation is also discovered between peak temperature and equivalence ratios; NO emission at the initial temperature of 525 K is 5.64 times, larger than NO emission at the initial temperature of 300 K. Thus, it is preferable to balance the effect of thermal efficiency and environment simultaneously when determining the optimal initial temperature range. The working parameter limits of divergent burner are wider than that of cylindrical one which contributes to reducing the influence of LCM concentration and volume fluctuation on combustion.

1. Introduction

Coal, an important resource in China, occupies approximately 70% of total Chinese primary energy [1–3]. In the process of coal mining, coal mine methane is the main factor affecting the safety of the exploitation. Gas extraction has been the dominant measure for controlling gas disaster [4]. With the development of mining technology, gas extraction volume increases year by year. For instance, the gas extraction volume reached 14.1 billion m^3 and the utilization volume increased to 5.8 billion m^3 in 2012, which increased by 23.2% and 20.2%, respectively. However, low concentration methane (LCM) accounts for more than 70% of the total gas extraction volume [5,6]. The utilization of LCM has been the biggest difficulty for coal mine methane, because the concentration is too low and fluctuating. Consequently, it is necessary to propose a new combustion method for using LCM efficiently and stably.

LCM (0–8%) is a typical low calorific gas because its calorific value is below 6.28 MJ/m^3. Premixed combustion technology in porous media has been considered as an effective method to use the low calorific gas. Compared with traditional combustion method, this technology combines several outstanding features, such as good flame stability, high combustion efficiency, extensional flammable limits and lower pollutant emissions [7–10]. Many studies focused on the porous media combustion from different aspects, including fuel gas additives, porous media physical parameters, different porous media combinations, etc. [11–16]. However, little attention has been given to the structure of burner. Some scholars also have studied cylindrical porous media burner [17–19]. Zhdanok et al. investigated the annular porous matrix of cylinder and sphere which can broaden the lean flammability limits and increase the combustion load [20,21]. Yamamoto et al. studied the combustion characteristic of cuboids porous media burner and depicted three-dimensional figures of rate, temperature and other physical quantity by numerical analysis method [22,23]. The structure of porous media has been focus of studies, while the optimal structure has not been found yet.

Solved by Fluent software, the mathematical and physical models were established on the basis of Bakry's experimental apparatus [24,25]. The model also considered the heat transfer between the gas and solid phases. The sensitivity study of combustion characteristics was conducted using the working parameters and initial temperature of inlet LCM. In addition, a cylindrical burner, the same inlet diameter as the divergent burner, was used to discover

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* Corresponding author. Tel.: +86 15862189252.
E-mail address: daihuaming666@163.com (H. Dai).

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the velocity upper limit law. It is of importance to design burner and control pollutant emissions.

2. Physical and mathematical models

The divergent burner studied in this paper is an axial symmetric structure. Physical quantity along its axial section only has a relationship with radius of cross section. Here the effect of circumferential angle can be ignored. Therefore, the three-dimension model is simplified as two-dimension one [18].

2.1. Physical model

Fig. 1 (left) shows the two-dimension (2D) structure of divergent burner. The inlet diameter is 20 mm, while the outlet one is 180 mm. In order to validate the predicted temperature, Al_2O_3 lamella was used as the porous media material [24]. Table 1 depicts the special physical parameters of the Al_2O_3 lamella [26]. Fig. 1 (right) presents the cylindrical structure with a 20 mm diameter.

2.2. Governing equations

Continuity equation

$$\nabla \cdot (\rho_g \vec{u}) = 0 \tag{1}$$

where ρ_g is the density of the gas, kg/m^3; and $\vec{u}$ the velocity vector of gas.

Momentum equation

$$\nabla \cdot (\varphi \rho_g \vec{u}\ \vec{u}) = -\varphi \nabla p + \nabla \cdot (\varphi u \nabla \vec{u}) + R_1 \tag{2}$$

where φ is the porosity of Al_2O_3 lamella; $R_1 = -\left(\frac{\mu}{K_1} + \frac{\rho_g}{K_2} |\vec{u}|\right) \vec{u}$ the pressure drop resulting from the porous media; k_1 the viscosity coefficient of fluid; and k_2 the inertial coefficient [27].

Gas phase energy equation

$$\varphi \nabla \cdot (c_{pg} \rho_g \vec{u} T_g) = \varphi \nabla \cdot (\lambda_g \nabla T_g) - \varphi \sum_i \omega_i h_i W_i - h_v (T_g - T_s) \tag{3}$$

Solid phase energy equation

$$\nabla \cdot (\lambda_{eff} \nabla T_s) + h_v (T_g - T_s) = 0 \tag{4}$$

where c_{pg} is the specific heat of the gas mixture, J/(kg · K); T_s and T_g the temperature of solid and gas, K; λ_g the gas thermal conductivity, W/(m · K); ω_i the molar producing rate of species i; h_i the molar enthalpy of species i, J/mol; W_i the molecular mass of species i; h_v the volumetric convective heat transfer coefficient, W/(m^3 · K); and λ_{eff} the effective thermal conductivity of porous media, W/(m · K).

$$\lambda_{eff} = 0.34691 - 0.00073672 \cdot T_s + 1.2052 \times 10^{-6} \cdot T_s^2 + 0.32345 \cdot u$$

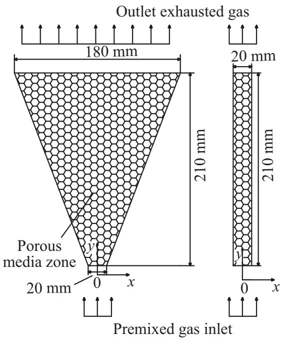

Fig. 1. 2D geometric model of the burner.

Table 1
Thermophysical parameters of porous media.

Parameter	Value
k_1 (m^2)	2.533×10^{-7}
k_2 (m)	1.223×10^{-2}
φ	0.42
h_v(W/(m^3 · K))	150,000

Species transport equation

$$\nabla \cdot (\rho_g \vec{u} Y_i) = -\nabla \cdot (\rho_g Y_i \underset{i}{\vec{V}}) + \dot{\omega}_i W_i \tag{5}$$

where Y is the mass fraction of the species i; and $\underset{i}{\vec{V}}$ the diffuse velocity of the species i.

State equation

$$\rho_g = \frac{\overline{W} p}{R T_g} \tag{6}$$

where p is the pressure of gas mixture, Pa; $\overline{W}$ the mean molecular mass; and R = 8.314 J/(mol · K) the universal gas constant.

2.3. Boundary conditions

Gas phase inlet ($x = -0.01$ m -0.01 m, $y = 0$ m) ($u = u_0$, $v = 0$, $Y_k = Y_{k,0}$, $T_g = T_0 = 300$ K)

Gas phase outlet ($x = -0.09$ m -0.09 m, $y = 0.21$ m) ($v = 0$, $\frac{du}{dx} = \frac{dY_k}{dx} = \frac{dT_g}{dx} = 0$)**

Porous media inlet ($x = -0.01$ m–0.01 m, $y = 0.01$ m)

$$Q_{in} = -\varepsilon \sigma (T_s^4 - T_0^4) - h_s (T_s - T_g) \tag{7}$$

Porous media outlet ($x = -0.09$ m–0.09 m, $y = 0.21$ m)

$$Q_{out} = -\varepsilon \sigma (T_s^4 - T_b^4) - h_s (1 - \varphi)(T_s - T_g) \tag{8}$$

where h_s is the convective heat transfer coefficient, and set as 500 W · m^{-2} · K^{-1}; T_0 the environmental temperature; and ε the apparent emissivity of the ceramic foam [26,28].

$$\varepsilon = 1/[1.0071 + 6.14885] \times 10^{-8} \cdot T_s^{2.5} - 9.5358 \times 10^{-10} \cdot T_s^3$$

At the burner outlet, the porous skeleton radiates toward a black body with T_b 673 K; σ is the Stefan–Boltzmann constant, 5.67×10^{-8} W/(m^2 · K^4). The burner wall was considered to be adiabatic and non-slip [26].

2.4. Numerical methods

The standard k–ε equation was used to depict the turbulence effect in porous media. Adopting the eddy dissipation concept (EDC) model, the turbulence-chemistry interaction can be ascertained in detail. In addition, a skeletal methane mechanism with 16 species and 41 reactions was imported to improve the prediction accuracy [29]. The coupling of pressure and velocity was solved by the SIMPLE algorithm with the second order upwind method used for the advection term in momentum and energy equations. In order to inspect the mesh independence, three types of mesh were built. And the simplest mesh, which has little influence on result, was employed to reduce the computing cost. Meanwhile, each parameter should be sufficient convergence.

In order to determine the combustible composition in LCM, the coal mine methane from Luling Coal Mine was measured by gas chromatography. The results (Table 2) show that the dominant combustible composition is methane and the ethane can be ignored for its negligible content. Therefore, the concentration of methane represents the combustible fuel concentration in coal mine methane.