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Premixed combustion of low-concentration coal mine methane with water vapor addition in a two-section porous media burner

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ABSTRACT

During the transport of low-concentration coal mine methane (CMM), water mist spraying into the pipeline is used to eliminate the risk of explosion, but it leaves abundant vapor in the methane. This study was aimed to explore the effects of water vapor addition on the low-concentration CMM combustion in porous media. Thereby, a 2D numerical model based on a two-section ceramic foam burner setup with high flame stability was established and multi-step kinetics mechanisms were imported to the model. In this paper, the effects of vapor concentrations on the temperature distribution, flame stability limit, and chemical reaction during low-concentration CMM combustion in ceramic foam were investigated. Results indicate that with the increase of vapor mole fraction in the inlet methane, the overall temperatures in the downstream section of the burner gradually decreased, while the vapor mole fractions were linearly and negatively correlated with the peak temperatures in the burner. A small amount of vapor was involved in the chemical reactions of combustion, and with the increase of vapor mole fraction, more vapor took part in the reactions when the vapor addition into the inlet methane was unchanged. As the vapor mole fraction in the low-concentration CMM increased, the velocity range of flame stability limit was gradually narrowed down. In addition, the lower limit of velocity changed very slightly and maintained at 0.13–0.20 m/s, while the upper limit dropped obviously. The key elementary reactions underlying the effect of vapor on combustion reactions were determined by defining the changing rate of peak reaction rate. Addition of vapor into methane affected the peak rate of each elementary reaction, and altered the area of axial region where elementary reactions occurred.

1. Introduction

Coal mine methane (CMM), also called coalbed methane [1], is a typical unconventional natural gas resource. Because the major combustible component of CMM is methane, CMM is a clean energy source from the perspective of energy, but is a potent greenhouse gas from the environmental perspective [2], as its greenhouse effect is 21 times that of CO_2 [3,4]. Thus, safe and efficient utilization of CMM is very significant for energy conservation and environmental protection. The quantity of CMM drainage in China was 18 billion m^3, and the utilized amount was 8.6 billion m^3 in 2015. Thus, the methane utilization rate was only 47.8%. The majority of CMM is unusable mainly because of the low concentrations of drained methane, and the frequent fluctuations in methane concentrations and flow rates, which together prevent the conventional techniques from efficient utilization of CMM. Compared with the traditional free flame combustion technology, the porous medium combustion technology is superior with a broader lean-burn limit range, higher burning efficiency, less pollutant emission, and faster flame speed [5–9], which are favorable for combustion and utilization of low-concentration CMM. Meanwhile, porous medium combustion applications also include porous medium engines, hydrogen production, thermoelectric convectors, heat exchangers, VOC oxidation, infrared heaters, and micro combustors. So far, the gas combustion characteristics in porous media is mainly studied from two aspects: porous medium structure and inlet fuel gas components.

Reasonably designing porous medium structures contributes to stabilizing the combustion flames and optimizing combustion characteristics. There are mainly two types of porous medium structures, including one-section and two-section burners, which receive much attention. The one-section burner is composed of one kind of porous medium structure. Though the singleness of the porous medium structure facilitates the arrangement of experiment platforms, the overall

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Nomenclature

c	specific heat [J/kg·K]
$D_{\|\|}^{d}$	thermal dispersion coefficient [m^2/s]
$D_{m\|\|}^{d}$	species dispersion coefficient [m^2/s]
$D_{m,i}$	diffusion coefficient of species i [m^2/s]
h	molar enthalpy [J/kmol]
k_1	penetrability coefficient
k_2	inertial coefficient
k	thermal conductivity [W/m·K]
k_{rad}	radiative heat transfer coefficient [W/m^2·K]
M	mean molecular weight
P	pressure [Pa]
Q	heat flux [W/m^2]
R	universal gas constant, 8.314 J/(mol·k)
S_i	source item
T	temperature [K]
T_0	ambient temperature, 300 [K]
T_{max}	peak temperature [K]
u	superficial velocity [m/s]
u_x	x-direction velocity [m/s]
v_y	y-direction velocity [m/s]
W	molecular mass
x	x-direction position [m]
y	y-direction position [m]
Y	local mass fraction

Greek symbols

α	extinction coefficient of porous media
γ	changing rate of peak reaction rate
ε	porosity
θ	water-bearing mole fraction
μ	kinematic viscosity [m^2/s]
υ	reaction rate
ρ	density [kg/m^3]
σ	Stefan-Boltzmann constant, 5.67×10^{-8} [W/m^2·K^4]
ξ_c	heat loss coefficient of radiation [W/m^2·K]
ξ_r	heat loss coefficient of conduction [W/m^2·K]
φ	equivalence ratio
ω	molar rate of production [kmol/s]

Subscripts

eff	effective thermal conductivity
g	gas
i	species number
in	inlet
s	solid
out	outlet
peak	peak temperature/speed
w	wall of the burner

structure design is very complicated and unpractical in order to stabilize the burning flames. Hoffmann et al. [10] built a one-section porous medium burning platform and succeeded in reciprocating gas flow by installing solenoid valves in the gas route. The reciprocating airflow could expand the lean-burn limit range of stable burning flames in the one-section porous medium. The minimum limit equivalence ratio of stable flames was 0.026, and the NO_x emissions under different working conditions in the burner were all lower than 1 ppm. The experimental results in this study are consistent with the numerical simulation results from Hoffmann et al. [11]. Contarin et al. [12] built the numerical model of a reciprocating one-section porous medium burner filled with 5.6-mm Al_2O_3 pellets, and embedded heat transfer units to the two ends of the packed bed. The dynamic reciprocating airflow could restrict the burning flames in the pellet packing bed. Contarin et al. [13] confirmed that the emissions of CO (4–10 ppm) and NO_x (< 15 ppm) in this type of one-section burners were extremely low. Bakry et al. [14–16] experimentally filled a diverging one-section porous medium burner only with Al_2O_3-lamella and improved the combustion performance by increasing the initial pressure and initial temperature of the inlet fuel gas. Zhdanok et al. [17,18] designed cylindrical and spherical burners embedded with one-section porous media, and through theoretical analysis and numerical simulation, found the ignition positions significantly affected the flame stabilizing position in both burners.

One-section burners are composed by one pore porous medium structure, and the burning flames are stabilized by the special settings such as burner shape and airflow direction. On the contrary, the overall structures of two-section burners are relatively simple, since the flame stay can be maintained only by combining two types of porous medium structures with significantly different pore scales according to the gas flow directions, which has been extensively confirmed [19–22]. In particular, the airflow inlet of a two-section burner was installed with small-pore porous materials, which could preheat the fresh airflow and prevent flashback [23]. Moreover, the airflow outlet was installed with large-pore porous materials, which promoted the complete burning and flame propagation. Hsu et al. [24] built an experiment platform of two-section porous medium by using partially-stabilized zirconia (PSZ) ceramic foam with significantly varying porosity, and found flames could be fixed near the interface of two-section porous media, and the equivalence ratio with stable flames was 0.41–0.68. Hsu et al. [25,26] also built a numerical model of two-section porous medium and studied the effect of porous material on the combustion flame stability. They studied the CO and NO_x emissions at the burner outlet and elaborated the importance of the combustion mechanism for model prediction. Based on a two-layer burner composed of 10 and 65 PPI (pores per inch) ceramic foam, Khanna et al. [27] found the CO, NO and NO_x emissions were very low and all increased with the increase of inlet gas flow rate. Mathis and Ellzey [28] built a two-section burner from 10 and 60 PPI ceramic foam and studied the effects of porous material (PSZ, zirconia toughened mullite ZTM) and porous medium height on the combustion characteristics. They found the CO and NO_x emissions were lower than 15 and 10 ppm, respectively [28]. Based on the numerical model built by Henneke and Ellzey [30], Barra et al. [29] established the porous medium model of two-section burner in order to obtain stable combustion flames. It was found that the porous medium material located at the upstream of the burner should be featured by low conductivity, low volumetric heat transfer coefficient, and high radiative extinction coefficient, while the porous medium material at the downstream should be characterized by high conductivity, high volumetric heat transfer coefficient, and intermediate radiative extinction coefficient. Gao et al. [31] built a two-section alumina packed-bed burner with different pellet diameters and found the two-section burner had an obviously wider working condition range with stable flames than one-section burners. Gao et al. [32] also expanded the two-section burner and by setting the 3-mm-pellet packed bed as the upstream section against flashback, investigated the temperature distributions and gas emissions (CO, NO_x, HC) when the downstream section was installed with 10 PPI ceramic foam, 13-mm-pellet packed bed, and 20 channel-per-square-inch (cpsi) honeycomb ceramic separately.

Besides the effect of porous medium structure, another research hotspot is the effect of inlet fuel gas composition on the combustion characteristics of porous media. The fuel gases from different industrial backgrounds (e.g. low-concentration CMM, landfill gas, syngas, biomass gas) are compositionally different, and thereby could significantly