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Research paper

Combustion characteristics of low-concentration coal mine methane in ceramic foam burner with embedded alumina pellets

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HIGHLIGHTS

- Ceramic foam burners with embedded alumina pellets were built.
- 13-mm pellets are suitable to be embedded in the spaces of 10-PPI ceramic foam.
- Start-up time is increased when the pellets were embedded in the ceramic foam burner.

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ABSTRACT

Ceramic foam as a rigid matrix is difficult to be embedded with various shapes of heat exchange tubes. In this paper, a ceramic foam burner with embedded alumina pellets was designed, which can set different shapes of tubes by taking advantage of the discrete pellets. An experimental system was built to study the effects of the pellet diameter and pellet location on the combustion of low-concentration coal mine methane (LCM). Results indicate that the heat transfer features of 13-mm pellets are more similar to those of 10-PPI ceramic foam compared with 6-mm pellets and 9-mm pellets. When arranged in upper section of the burner, the 13-mm pellets preserve the combustion heat, which helps to move the flame stabilization position to the upstream of the burner. In addition, the start-up time in the burner with the upper 13-mm pellets is longer than that with the intermediate 13-mm pellets. The total NO_x emissions of the studied burners are improved with the increasing inlet velocity, while the CO emissions first decrease and then increase. The HC emissions of the ceramic foam burner with embedded pellets are between those of the pellet burner and the ceramic foam burner.

1. Introduction

During coal mining, coal mine methane (CMM) is the main reason for the accidents of gas explosion, coal and gas outburst, and gas combustion [1]. The technology of CMM extraction has been developed in order to remove the CMM from the coal [2]. As the coal production in China increased to 3.7 billion tons in 2013, the CMM extraction volume reached 15.6 billion m^3. Because low-concentration CMM (LCM) accounts for nearly 70% of the total volume, the utilization of CMM becomes a big challenge [3]. Direct discharge of LCM (comprising of methane) will bring many environmental problems and result in resource waste. However, the traditional combustion technology is unable to utilize LCM effectively. In comparison, the premixed combustion in porous media combines several outstanding features, such as high combustion efficiency, extended lean flammability limit, low pollutant emissions, and high flame stability [4–6], which are very suitable for the utilization of LCM.

During the development of porous media combustion, the selection of porous structure has received high attention from scholars because porous structure as the key characteristic of porous material greatly influences the combustion performance of porous media burner. Presently, the main porous structures are comprised of reticulated foam and packed bed [7]. Specifically, the reticulated foam is characterized by the high porosity (70–90%), so that the pressure drop is very low when the gas passes through the

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Nomenclature

d	mean cell size (m)
k	thermal conductivity (W/m K)
m_F	mass of fuel (kg)
m_O	mass of oxygen (kg)
T	temperature (K)
v	inlet velocity of premixed gases (cm/s)
Greek symbols	
α	extinction coefficient of porous media
ε	porosity
σ	Stefan–Boltzmann constant, 5.67×10^{-8} (W/m^2 K^4)
φ	equivalence ratio
Subscripts	
sto	stoichiometric fuel-oxygen mass ratio
exp	experimental fuel-oxygen mass ratio
f	ceramic foam
p	pellets
con	conduction
rad	radiation
eff	effective

foam [8]. The specific surface area of the reticulated structure is so large that it greatly enhances the internal heat convection [9,10]. In addition, the radiation and conduction performances are high due to the optical thickness with the order of 10 pore diameters [11]. These great performances of reticulated foam have attracted the interest of many researchers [12–18]. Hsu et al. [16] studied, experimentally and numerically, the premixed methane combustion in reticulated foam (consisting of partially stabilized zirconia). A wider equivalence ratio range (0.41–0.68, by experiment) was determined in the reticulated foam burner and the maximum flame speed in this burner is obviously higher than the premixed free flame speed. Francisco et al. [19,20] designed the experimental system of porous media combustion and found that the stability range in reticulated foam burner was enlarged by adding hydrogen to the inlet gas. Meanwhile, the CO and CH emissions were greatly reduced when the reticulated foam burner was located in a confined heated environment. Catapan et al. [13] proposed a non-uniform velocity profile mechanism for flame stabilization in an experimental reticulated foam burner and found that the flame front has a conical shape for lower reactant flow rate and the inlet non-uniform velocity contributes to preventing the flame flashback. Gao et al. [21] experimentally studied the combustion characteristic of premixed methane/air mixtures in different porous media (foams, pellets, and honeycombs). From their experimental results, the flame stability limits are decreased in the order of 10-PPI (pore per inch) foams, 13-mm diameter pellets, and 200 CPSI (channel per square inch) honeycombs. In addition, the flame temperature of the foams was obviously lower than those of the packed beads and honeycombs due to the significant heat transfer in reticulated foams burner, which contributes to reducing NO emissions. Besides the merits of reticulated foam in heat transfer, however, the reticulated foam as a rigid matrix is unable to change its shape. Thus, a manufactured reticulated foam cannot match with a complicated-shaped burner, and many spaces among the tubes will occur when the reticulated foam is embedded with heat exchange tubes to extract the combustion heat [31].

Compared with the rigid reticulated foam, the packed bed formed by discrete particles is suitable for a burner of any shape and for being embedded with heat exchange tubes. The general material of a packed bed is alumina pellet with the diameter of 5–20 mm [22–24]. Many scholars have studied the premixed combustion in packed beds formed by pellets owing to the merits of changeable packing shape [25–32]. Xiong et al. [31] experimentally studied the influence of spacing between the heat exchange tubes and different packed bed materials on the combustion characteristics, and found that the packed bed with embedded heat exchange tubes bring higher heat exchange efficiency, lower pollutant emission, and a more compact structure compared with the traditional heat exchange method. These experimental results were later used to validate the theoretical models [28,29,32]. Liu and Hsieh [27] found that the flame temperatures (1000–2000 °C) decrease by 200 °C between the equivalence ratio of 0.472 and 0.598 compared with the corresponding adiabatic temperature when the ceramic pellets (diameter of 7.7 mm) are embedded with heat exchange tubes in the experiment. Trimis and Durst [30] built the combined burner and heat exchanger system with the discrete pebbles (diameter of 9 mm), and found that the volume of the system is of the order 10–15 times smaller than the most existing burner and heat exchanger systems. Jugjai and Sawananon [26] embedded heat exchange tubes in a packed bed of a reciprocal flow combustor and found that the thermal efficiency increases by nearly 80% compared with the efficiency of heat exchanging in exhaust gas. Contarin et al. [25] numerically studied the reciprocal flow combustor with the cooling tubes embedded in the two ends of the packed bed and found that the tubes contribute to stabilizing the flame in the central zone. However, packed beds formed by pellets are characterized by relatively low porosities (in the range 30–50%) depending on pellet size, which lead to a higher pressure drop through the packed bed [7]. In addition, the heat transfer in the packed bed is weaker compared with that in the reticulated foam, which is useless to extend the stability limits.

Porous structures of reticulated foam and packed bed have respective advantages when used in the porous media combustion. However, the porous media burners possessing both the merits of reticulated foam and packed bed, have scarcely been found in the previous literatures. In order to combine the high heat transfer performance of the reticulated foam and the shape changeability of the packed bed, reticulated foam burners embedded with discrete pellets were designed. In the new burners, the heat exchange tubes can be easily placed in the discrete pellets region and the spaces between the tubes and porous media will not occur. The ceramic foam of silicon carbide (SiC) and the alumina pellets are the dominant reticulated material and packed bed material respectively owing to their stable features [5,11,18]. Thus, an experimental system was built to characterize the combustion in ceramic foam burners embedded with alumina pellets. Considering the influence of pellet diameter on the combustion [33–35], we embedded the burners with pellets of different diameters. In addition, the positions of alumina pellets in the ceramic foam were considered since the heat exchange tubes could be located in the flame zone or the combustion products zone [29,31]. This paper will provide the CMM utilization engineering with a theoretical reference on solving the space problem of a ceramic foam burner with embedded heat exchange tubes by filling alumina pellets.

2. Experiment

2.1. Experimental materials

2.1.1. Porous media

Table 1 shows the detailed pore sizes used to study the porous media combustion by some scholars. It is found that the ceramic