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Ultra-low calorific gas combustion in a gradually-varied porous burner with annular heat recirculation

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ABSTRACT

Experimental studies on premixed combustion of ultra low calorific gas (LCG) in an axial and radial gradually-varied porous media burner with annular for heat recirculation were conducted. The effect of firing rate for different heating value of low calorific gas on temperature profiles, flames stability and CO emission was studied. The flame stability limits increased while the CO emission decreased with the increase of heating value of LCG. The flame located near the front of the inner tube at the upper flame stability limit and the corresponding temperature profiles decreased along the flow direction. The flame location moved from the upstream to the downstream with the increase of firing rate, and the corresponding temperature profiles of upper flame stability limits were much uniform than that of lower flame stability limit. The combustion and flow characteristics could be improved by using an annular heat recirculation, and an ultra-low calorific gas of 1.4 MJ/m^3 can burn in the present porous burner.

1. Introduction

Low calorific gas (LCG) is the combustible gas which calorific value is below 6.28 MJ/m^3, such as biogas produced by anaerobic action of the bacteria with the waste, syngas produced from gasification of biomass and fossil fuels, coke oven gas (COG) produced in steel production, mine ventilation gas in the process of coal mining. A significant amount of primary energy can be saved and the hazardous emissions can be reduced by effective combustion of these low calorific gases (LCGs). Combustion of LCGs may have many technical difficulties associated with ignition and stability due to the fluctuating composition and high inert content. Combustion with EGR (exhaust gas recirculation) is one of high efficiency and low-pollutant combustion methods, which has widely been applied. For example, Yu et al. [1,2] studied the possibility of using EGR method for a small-scale household boiler, and indicated that the EGR method is advantageous from the standpoint of reducing emissions and improving the combustion stability. However, the system is complex for recycling the heat back to the incoming reactants by using a recuperator or a regenerator. Combustion in porous media is known as an effective method for utilization of energy by recycled the heat back to the premixed reactants without any other equipment. There are several outstanding features of porous burner compared with traditional combustion method, such as high power modulation, good flame stability, compact size, low pollutants emissions, etc. Wood et al. [3] reviewed the related studies and indicated that porous burners were capable of burning low-calorific value fuels and lean fuel/air mixtures without flame, potentially allowing the exploitation of current wasted energy resources. In order to utilize low calorific gases cleanly and effectively, many researchers have done much work to investigate combustion characteristics in porous media burners.

Two-section porous burners have received a great deal of attention for its good flame stabilization in the last decades. It reported that the flame could easily stabilize at or near the interface between two blocks of different ceramic porous media [4–9]. The interface where the pore size changes suddenly serves as an effective flame holder, providing stable operation over a range of conditions. Gao et al. [10–12] experimentally investigated the effect of porous media with various arrangements on the flame stability. It is found that the foams have a better flame stability than that of pellets and honeycombs, the flame stability region enlarged with increasing of thermal conductivity but decreased with increasing of pore density of foams. Mujeebu et al. [13] developed two compact premixed LPG burners based on submerged and

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surface combustion modes, namely, SSB (surface stabilized burner) and MSB (matrix stabilized burner). The thermal efficiencies of CB (conventional burner), MSB and SSB are 47%, 59% and 71% for a thermal load of 0.62 kW, respectively. Wang et al. [14] studied the effect of the burner inlet gas flow rate, equivalence ratio, and diameter of alumina pellets on the combustion temperature distribution along the burner axis and the combustion wave velocity using a two-layer burner filled with different diameter alumina pellets. The results showed that the critical equivalence ratio corresponding to the superadiabatic combustion was bigger for the smaller pellet diameter or higher inlet air flow rate.

The two-layer porous burners were also performed for ultra-low calorific gas combustion in the previous works. Gao et al. [15] studied biogas combustion in a two-layer porous burner packed with spherical alumina pellets and indicated that both the stable flame region and the flame temperature decreased with increasing CO_2 concentration. Keramiotis et al. [16,17] evaluated the performance of a rectangular two-layer porous burner fueled by simulated biogas (60% CH_4 and 40% CO_2 by volume). CO_2 presence in the fuel mixtures was found to increase CO emission by around 50% and reduce NO_x emission by 50–60% in comparison to pure methane operation. Al-attab et al. [18] experimentally investigated the producer gas combustion in a two-layer packed bed burner and reported that the minimum emissions of CO and NO_x were 6 and 230 ppm, respectively. Dai et al. [19,20] studied the combustion characteristics of mine ventilation gas in a two-layer ceramic foam burner, and concluded that the total temperature increases and appears to be more homogeneous with the heat loss wall as the burner diameter increases. Huang et al. [21] simulated three typical low-calorific gas mixtures in a two-layer porous burner, and the results showed that the convective coefficient of upstream has more influence on temperature behaviors than that of downstream. Panigrahy et al. [22] numerically and experimentally analyzed combustion of LPG (liquefied petroleum gas) in a two-layer porous radiant burner. It reported that the thickness of the preheating zone has insignificant effect on CO emissions, preheating temperature and lean flammability limit. Sharma et al. [23] employed a two-layer burner in a kerosene pressure stove and found that the highest efficiency of the stove with porous media is about 10% higher than the average thermal efficiencies of the stoves available in the Indian market.

Adding high calorific gas such as hydrogen is another effective method for promoting the combustion in porous burner. Tseng [24] studied the effects of hydrogen addition to natural gas and found that the lower lean limit be extended from 0.33 for pure CH_4 to 0.26 for H_2/CH_4 mixture in the porous burner. Similarly, Rortviet et al. [25] reported that hydrogen addition to natural gas is benefit to flame stability. Gauthier et al. [26,27] indicated that the addition of hydrogen resulting in the decreased importance of the prompt pathway and NO formation. Alavandi and Agrawal [28] investigated the combustion of hydrogen–syngas/CH_4 blended fuel in a two-section porous burner and reported that both CO and NO_x emissions decreased with the increase of H_2/CO content in a fuel mixture. Francisco et al. [29,30] studied the effect of fuel composition on flame stability and pollutant emissions in a porous burner, and indicated that the upper flame stability limits increased and the stable ranges enlarged with the increasing H_2 percentage in hydrogen-rich gaseous mixtures.

Most of pervious works focused on combustion of low-calorific gas by improving the structure of porous media or adding high calorific gas in porous media burner. A new porous burner is designed for utilization of ultra-low calorific gas by recirculation heat from the combustion products with annulus structure. The present combustor is composed of concentric-tubes, where the reactants enter into the annulus and the product gases exit from the inner tube. The porous burner is examined with simulated ultra low calorific gases to find the upper and lower flame stability limits. In particular, the effects of the firing rate on the flame stability limits, flame temperature profile, and pollutant emissions are discussed.

2. Experimental section

2.1. Experimental setup

A schematic diagram of the experimental apparatus is shown in Fig. 1, which consists of four main parts: a fuel/air supply system, a preheating gas supply system, a porous burner and a data acquisition system. Methane and nitrogen are stored in two high-pressure bottles of 13 MPa, and regulated by two mass flow controllers (SY-9312D, 0–1.0 L/min, SY-9322D, 0–30.0 L/min, manufactured by Shengye Co. of Beijing), respectively. The air is supplied by a compressor and connected to an air storage tank to avoid pressure fluctuation, then pass through a dryer and regulated by a mass flow controller. The fuel and air then entered into the premixer II for fully mixing before introduce into the combustion chamber. The mixture of low calorific gas/air is preheating in the annulus and burning in the inner tube of the burner. The preheating gas supply system is used to preheating the porous media before the fuel/air supply switch into the burner. The liquefied petroleum gas (LPG) is used as a fuel gas in the preheating supply system, which is supplied from a high-pressure bottle of 13 MPa, then regulated by a glass rotor controller (LZB-3, 10–1000 mL/min, manufactured by Yuanda Co. of Yuyao). The air in the preheating gas system is supplied by the same storage tank, regulated by another glass rotor controller (LZB-6, range 60–600 L/min, manufactured by Yuanda Co. of Yuyao). The liquefied petroleum gas and air are fully mixed in the box of premixer I before introduce into the combustion chamber.

The porous burner is an annular tube as shown in Fig. 2, which consists of two concentric stainless steel tubes with a diameter of 74 mm and 50 mm, respectively. The annulus between inner tube and outer tube is filled with stainless steel fibers for increasing heat capacity. A 25 mm thickness perforated plate is located at the front of inner tube for homogeneous premixing. Two types of SiC foams (a circular plate with an inner diameter of 25 mm and an outer diameter of 49.5 mm, and a plate with a diameter of 25 mm) were located adjacent to the perforated plate, each plate of SiC foam has a thickness of 30 mm and the arrangement is shown in Fig. 2. The pore density of the foams is ranged from 15PPI to 40PPI (pores per inch) and the porosity is about 80% in present burner, and the photo is displayed in Fig. 3. The gap between the inner tube and circular plate of foams is filled with mud for preventing the leakage of fuel/air mixture. The burner is covered by a high-temperature ceramic fiber with a thickness of 20 mm to minimize the heat loss.

The temperature distributions of porous burner are measured by nine K-type thermocouples located at the wall of the inner tube along the axial direction with an interval of 15 mm, and the corresponding signals were detected and recorded using a data acquisition system (Agilent: 34972A). The emissions of exhaust gases were sampled by a stainless steel probe at the burner exit, and the CO concentration in the combustion products was measured by a real-time gas analyzer (Testo 350M/XL).

2.2. Experimental procedure

The mixture of LPG/air (preheating gas supply system) was firstly ignited at the exit of the burner with an equivalence ratio, and the flame front was reversely penetrated into the porous media of the inner tube and moved to the upstream. Then, the preheating