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Experimental investigation of submerged flame in packed bed porous media burner fueled by low heating value producer gas

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ABSTRACT

Combustion inefficiencies and high pollutants emissions keep motivating researchers to enhance combustion technology. Producer gas fuel from biomass gasification with its low heating value and high CO content requires a special combustor design for efficient burning. Porous media burner (PMB) has been widely investigated and proven to be well suited for low heating value fuels lean combustion. This study aims at performance investigation of PMB fueled by producer gas from biomass gasification. A downdraft gasifier system along with a PMB burner and heat recovery unit has been developed. The PMB comprises two layers of 10 mm and 20 mm diameter upper and lower alumina spheres packed, respectively. With PG heating value of about 5 MJ/m^3, lean to ultra lean stable combustion was achieved with equivalence ratios (Φ) in the range of $0.33 < \Phi < 0.71$. Combustion layer temperature was in the range of 1300–1550 K. The lowest recorded emissions from the PMB were 6 ppm and 230 ppm for CO and NO_x respectively. The heat recovered from the burner was utilized in hot air production of 7 kW$_{th}$ that can be used for drying process in small industries. Maximum heat recovery heat exchanger effectiveness was about 93% with overall system efficiency of 54%.

1. Introduction

Combustion is a method of converting energy stored in the fuels to produce heat. This highlights the importance of maximizing the combustion efficiency since any undesired energy is considered wasted. Therefore the utmost concern is to maximize the recoverable heat and increase the efficiency of combustion systems. As the issue of fossil fuel depletion became more alarming, it accelerated research to increase performance of present equipment and develop new equipment to operate with alternative fuels. Producer gas (PG) from biomass gasification is one of the alternative fuels being investigated. It is more adaptable and efficient compared to raw solid biomass in combustion. Combustible substances in PG are mainly hydrogen, carbon monoxide and methane. However, for air gasification, PG is diluted with nitrogen resulting in a significant drop in the gas heating value. PG cannot be burnt efficiently in conventional burner due to its low heating value that requires a good mixing with air and also the low burning velocity of CO that requires longer residence time. Thus, new combustor designs have to be investigated to cope with PG combustion requirement. One of the designs is the cyclone combustor that provides an excellent air–fuel mixing with long residence time for PG combustion. Non-premixed atmospheric cyclone combustor for PG combustion have been studied [1,2]. Al-attab and Zainal [3,4] have studied the performance of premixed PG-air pressurized cyclone combustor in a micro gas turbine system.

Porous media burner (PMB) is an alternative design in combustion technology introduced by Weinberg in 1971 [5]. Early studies focused on the use of liquid fuels such as Heptane in 1995 [6], Kerosene in 1998 [7] and Ethanol in 2005 [8]. The use of PMB technology can enhance liquid fuel evaporation and combustion with a significant drop in pollutants emission [9]. In a recent study, heptane fuel combustion was investigated but in a meso-scale burner [10]. Many researchers have found that PMB has the capability to sustain lean combustion of medium heating value gases such as methane and propane [11]. PMB has also the ability of operating efficiently in lean combustion of low heating value gas fuels [12–15]. PMB technology has been investigated for a wide range of applications such as cooking stoves [16–20], boilers [21,22], Stirling engines [23], industrial wide plate heaters [24] and small scale co-generation systems [25]. Numerous studies on PMB performance with different gas fuel composition have been conducted using simulation and numerical modeling techniques [26–36].

There are generally two categories of PMB: the single-layer and two-layer PMB. The single-layer PMB is used to sustain the flame

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within the cavity of porous media for recirculation of excess enthalpy during combustion [37]. It is capable of producing high temperature despite lean combustion. However, limited research was done on single-layer PMB because it is prone to flashback [38]. A two-layer PMB consists of porous media with different pore sizes and porosities for both layers [39,40]. The first layer (the upstream layer) usually consists of porous region with high pore density (ppcm) ranging from 15 to 35 ppcm in the foam porous media [41–44]. As the first layer has tiny pores, the flow velocity is much higher than the combustion layer. Consequently, lower flame speed will not propagate in reverse direction that causes flashback [14]. Flashback is characterized by Peclet number, $Pe = S_L d_m c_p \rho_g / \lambda_g$ where S_L is the free laminar flame speed, d_m is the equivalent pore diameter, c_p, ρ_g and λ_g are the specific heat, density and thermal conductivity respectively of the gaseous mixture [45]. When $Pe < 65$, the flame extinguishes in the first layer and flashback is effectively prevented. Therefore, it is often called flame quenching zone [12], flame arrestor or flame holder [39]. This region is sometimes regarded as the preheating zone as heat from the combustion is claimed to be able to preheat the incoming air–fuel mixture.

The second layer of the porous media consists of larger pore size. Porous media with pore size of 4–5 ppcm is commonly used. This layer serves as the combustion zone where the flame usually stabilises close to the interface between the first and second layer. Therefore, the condition of second layer must fulfil the criterion of $Pe > 65$ [45]. It serves as solid–gas heat transfer medium to enhance heat transfer from the hot solid medium to the inlet fuel and hot combustion gas to the solid medium. The process of the flame heating up the porous media and the hot porous media heating up the inlet mixture forms a cycle of heat recirculation that takes place continuously. The concept of excess enthalpy recovery results in temperature exceeding the adiabatic flame temperature [11] often called superadiabatic combustion. It provides high rate for the conversion of CO into CO_2. At the same time, it provides less residence time for the combustion products to travel in the high temperature region that reduces the conversion of N_2 to NO_x, thereby, reducing the emissions [39]. Many studies have focused on methane [41,46–48] and also LPG [16–20,25] lean combustion in PMB with equivalence ratio ranging from 0.60 to 0.95. The maximum temperature in the combustion section is generally higher than 1500 K with NO_x and CO emissions usually below 50 ppm. Other studies investigated the ultra lean combustion of methane in PMB with equivalence ratio below 0.6 [24,49]. LPG fuel ultra lean combustion in the range of 0.6–0.47 equivalence ratio was also investigated [49], and a significant drop in NO_x and CO emissions below 10 ppm was noticed. In general, ultra lean combustion causes a drop in combustion temperature below 1500 K. Methane has better lower limit of stable flame compared to propane [42]. However, propane is capable of sustaining flame at higher firing rate than methane. Besides that, propane combustion tends to produce higher emission than methane [14]. Bakry et al. [50] have investigated the effect of air preheating and pressurizing the PMB on CO emission. With premixed methane-air and equivalence ratio in the range 0.6–0.35 a significant drop in emissions below 10 ppm was observed. In another interesting approach, an LPG fuelled PMB was tested in a wide equivalence ratio range of 0.7–1.3, and maximum radiation efficiency was found to be in the rich fuel zone ($1 < \Phi < 1.1$) [51]. Although CO emission was not reported, NO_x emission was 20 ppm.

One of the important aspect that has to be taken into consideration in a PMB design is the material of the porous media. Materials thermal conductivity and radiation properties can affect the burner performance considerably. One of the common arrangements is the use of porous foam or porous cake as the porous media. However, despite the simplicity in its fabrication process, thermal and mechanical failure leads to a periodic replacement of the porous media. Another arrangement is to use a packed bed porous media made by stacking discrete particles, such as alumina balls, in a burner to form a bed of porous media that constitutes certain porosity. The balls are known to have enhanced durability as they are not caged in rigid matrix. It is more flexible compared to ceramic foam because maintenance and modification of balls height can be done easily.

Several types of ceramic foam materials have been compared for PMB such as Yttria-stabilised zirconia–alumina (YZA) and zirconia-toughened mullite (ZTM) [41], SiC and alumina [12] and alumina, zirconia, iron–chromium–aluminium (FeCrAl) and SiC [47]. The effect of material shape on PMB performance was also investigated. Gao et al. [48] compared the performance of alumina foam, honeycomb and ball pack at similar pressure drop level. Alumina pellets and foams were also compared by Xie et al. [49]. Two-section alumina balls packed bed PMB was also investigated and it was found that packed bed PMB possessed similar characteristics as the porous foam PMB [45].

As for the fuel type, wide range of medium and low heating value fuels were investigated, however, most of the studies used simulated gas mixtures to study the performance of PMB. Landfill gas and medical waste pyrolysis gas compositions were simulated by varying CH_4 and H_2 percentages in N_2 [12]. It was found that the blow off limit of the mixture was at 26% methane. The blow off limit increases when firing rate increases. However, preheating the inlet air–fuel mixture enhanced the blow off limit to 20% methane. Similarly, simulated biogas was studied with 60% methane and 40% CO_2 in a two-layer PMB with equivalence ratio in the range of 0.7–0.9 [15]. The high CO_2 content in the fuel resulted in high CO emission of about 300 ppm which is 50% higher compared to pure methane fuel operation. Francisco et al. [13] have simulated mixtures of CH_4, H_2, CO, CO_2 and N_2 as the common PG compositions with heating value varying from 4.5–5 MJ/kg. The study concluded that increasing H_2 percentage enhances the burner stability significantly unlike the other gas composition with maximum temperature of about 1473 K. Similar experimental attempts were done by Alavandi and Agrawal [14] with simulated PG. CH_4 volume percentage was varied from 0% to 100%, Whilst CO and H_2 percentage were varied up to 50%.

It can be concluded from all the aforementioned experimental studies that the use of PMB technology for LHV gas fuels combustion has a significant effect on lowering CO and NO_x emissions for a very wide equivalence ratio range. However, most of the studies on LHV gas fuels used simulated gases with different mixing ratios, and there is gap in the studies on PMB performance with producer gas generated from biomass gasification. The PMB performance might change due to the contamination with tar and ash particles in the actual PG fuel. Also, testing the burner in an online operation with a gasifier gives a new experience on combustion stability with possible fluctuation in PG quality and composition during the operation. Thus, the current study incorporated a biomass gasification system with the PMB with two layers of different diameter alumina balls.

2. Experimental setup and procedures

A stratified throatless downdraft gasifier system along with a porous media burner and a shell-and-tube heat recovery unit were developed at the School of Mechanical Engineering, University Sains Malaysia. The downdraft gasifier was a 100 cm height and 15 cm diameter throatless type, operated in a suction mode and fueled by rubber wood chips with 4 kg capacity. Air was induced at the top and preheated in an air jacket before entering the gasifier. The producer gas was passed through an expansion box to cool the gas and remove large particles, and then it was induced