AEC006

An Influence of Pore Density on Flame Stabilization for LPG Porous Burner

Arwut Laphirattanakul[1], Ponepen Laphirattanakul[2,*], and Jarruwat Charoensuk[2]

[1] Department of Mechanical Engineering, Faculty of Engineering, Mahanakorn University of Technology, Bangkok, 10530, Thailand
[2] Department of Mechanical Engineering, Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang, 1 Chalongkrung Rd., Ladkrabang, Bangkok, 10520, Thailand
* Corresponding Author: jaja_kmitl45@hotmail.com, +6680-900-8880

Abstract

The flame stabilization of modified premixed LPG burner for ceramics industry with different density of porous media was investigated within operation range of 1-5 L/min. By maintaining the flame to be of cone shape which was desirable for this particular application, ignition took place inside the porous domain and propagated downstream. To achieve this, the porous foams, made of alumina with pore density of 15 and 20 ppi, were constructed in cylindrical geometry and replaced for an iron cast conventional burner. With this unique design the secondary air could be induced naturally. Flame visibility was observed in addition with the gas mixtures temperature profile at different fuel-air mixture ratio prior to combustion. It was found that variation in pore density could bring about significant change in combustion characteristic. The smaller pores created higher pressure drop than the bigger one leading to fuel rich combustion, one of instability factor. By observing visible flame, the ceramic foam with 20 ppi could not entrap the flame, especially at high flow rate, thus failed to preheat the up-coming fuel-air mixture. In contrary in the case of 15 ppi, the flame was well stabilized in the media between the operating range of 1-3 L/min, indicated by a bright illumination. Recirculation of heat by means of radiation and conduction promoted the flame stabilization in porous media. At LPG feeding rate greater than 3 L/min, flame lift-off took place on both burners corresponding with low temperature of unburned mixture. This indicated that S_L strongly played an important role on combustion stability, while a direct effect of porous structure on flame stability was not clearly observed within the scope of this work. The results of flame produced from propane-air mixture on both cases of burner could not propagate within medium at low S_L which correlated with $\Phi > 4$.

Keywords: Porous Burner, Pore density, Premixed burner, Alumina foam, Flame stability

1. Introduction

Combustion has been a main heat source for many industrial sector, including ceramics industry. In baking process, the high efficiency of combustion for sufficient temperature distribution was significantly required as well as low emission. A conventional burner currently using in this industry is premixed LPG burner with self-entrainment of primary air. It, however, produces remarkably long and oscillated diffused flame, especially at low operation range, due to lacking of primary air induction. Meanwhile, sufficient amount of air is found at high operation range, when the jet is provided with high speed.

Recently, there has been an active research on developing LPG injector concerning enhancement of primary air entrainment. The injector was designed operating on balancing between spring and fuel feeding forces. An annular exit area could be characterized following flow rate creating high speed jet particularly at low fuel consumption. This led to higher entrainment as comparing to a simply circular exit area. Therefore, the combustion with stability was occurred. However, the burner still provided non-uniformed temperature distribution and also high emission [1-4].

From literature survey, porous media has been an interested issue for improving combustion performance particularly on gaseous burner. Comparing to those of free flame, porous burner can produce higher burning rate, wider operation range and can also operate with low calorific fuel. These advantages are resulted from complicated structure of porous promoting self-recuperation and dispersion of heat. The heat will effectively transfer from products to reactants through gas and solid matter via heat conduction and radiation modes. This causes a preheated upcoming mixtures to react more efficiency with fuel[5],[6]. Moreover, porous burner was strongly claimed giving an effective flame stabilization. In the other words, it reduces the happening of flash back and lift-off due to tortuous structure. However, there has been some parameters that the combustion stability was relied on.

To achieve flame stability, there is an indicator expressing the limitation of combustion stability in porous media, Péclet number (Pe). This indicator was contributed from relation between gas and solid properties following Eq.(1)

$$Pe = \frac{S_L d_m C_p \rho}{\lambda} \tag{1}$$

Where S_L is laminar flame speed, d_m is effective diameter of average hollow space and C_p , ρ , λ are specific heat capacity, density and thermal conductivity of gas mixtures, respectively. From previous work [7], the critical value of Pe for identifying the limitation of stability of lean hydrocarbon-air mixtures was 65. The flame usually lifts and detaches above the medium when the range of Pe less than this specific value.

In aspect of emission, great distribution of temperature owing to conduction mode in porous domain totally helps on hot spot reduction, which is the caused of thermal NO_x. The self-recuperative mechanism also leads to elimination of carbon radical, thus CO reduction [5-7].

According to advantages on combustion performance of porous medium, there are many publications concerning the application on this matter for gas burners. Almost experimental works were, however, operated by forcing the controlled ratio of mixture into an insulated chamber. By considering the characteristic of conventional ceramics burner, the porous medium in this work was combusted naturally within stagnant air.

The cylindrical alumina foam was adopted on LPG burner to basically investigate an effect of pore density on gas premixed characteristics and also flame stability. The experiment was arranged by choosing two value of pore density at 15 and 20 ppi, subject to commercial availability, on the same fuel consumption range. The discussion would be drawn on temperature of gas mixtures and visual flame. In addition, percent premixed for combustion was also monitored in order to observe effect of this parameter on entrainment in a premixing chamber. It was because the premixed combustion obtained the primary air from natural entrainment correlating with fuel injection rate.

2. Experiment set-up

The experiment unit in this work was separated into three parts, shown in Fig.1, including fuel injector, mixing tube and burner. LPG containing of, 70% of propane and 30% of butane, was injected through nozzle with the consumption range of 1-5 L/min. This caused natural entrainment of primary air to the mixing tube. In order to gain more accumulative air in premixed chamber, the modified nozzle was adopted [1]. While secondary air was induced diffusively at combustion zone.

From literature review, the foam structure of porous medium was claimed providing widest operation range comparing to the others (honey comb and packed bed) [8]. Therefore, the Alumina foam (Al_2O_3) with 15 and 20 ppi, as shown in Fig.2, were carved into cylindrical structure having the same diameter and height with the conventional burner. Both medium was proved having the porosity of, approximately 0.9. They were placed instead of a conventional burner to obtain performance assessment. Moreover, ceramics fiber was inserted under porous medium to protect the splitting of flame at the bottom.

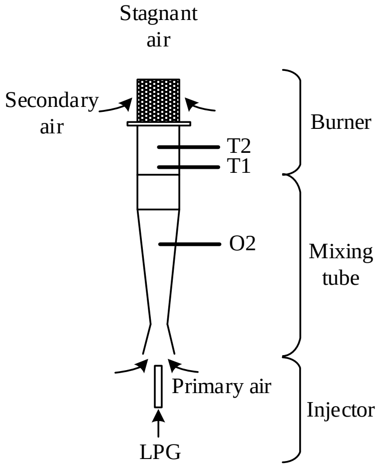


Fig.1 Diagram of premixed LPG burner

Fig. 2 Porous media with 15ppi (left) and 20ppi (right)

The temperature of incoming gas mixtures was monitor by two positioning of thermocouple indicated as T1 and T2 in Fig.1. The distance from burner port and each other was 4 cm. Thermocouple type K connected with YOKOGAWA XL100 data logger (accuracy including thermocouple is ±1°C). The oxygen percentage at mixing tube was measured by testo 350XL flue gas analyzer (accuracy ±0.8% by volume). The recorded data of oxygen concentration was then calculated into percent premixed by following the chemical equation:

$$0.7C_3H_8 + 0.3C_4H_{10} + a\left(O_2 + 3.76\,N_2\right) \rightarrow Mixtures \quad (2)$$

when

$$a = \frac{X_{O_2}}{1 - 4.76X_{O_2}} \quad (3)$$

Therefore, percent premixed can be calculated by:

$$\%\,premixed = \frac{4.76a \times \dfrac{MW_{air}}{MW_{LPG}}}{AF_{stoi}} \times 100 \quad (4)$$

Where X_{O_2} is fraction by volume of oxygen in mixing tube, MW_{fuel} and MW_{air} are molecular weight of fuel and air, respectively and AF_{stoi} is stoichiometric ratio for LPG.

3. Results and Discussion

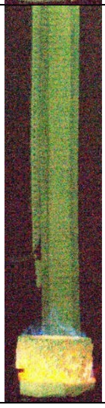
L/min of fuel	1	2.5	3	5
15 ppi				
20 ppi				

Fig.3 Visual flame of 15 and 20 ppi porous burner

As generally known, porous media has an ability on flame stabilization as can produce higher flame speed than those of free flame, approximately 10 times[7]. Flame stability in porous media is defined as the propagation of flame within the medium, hence, illumination of solid is observable. When stabilization is taking place, the heat from reaction zone will be circulated therein due to contribution of two modes of heat transfer.

Fig.3 shows visual flame produced from 15 and 20ppi porous burners with fuel variation. The four flow rates of fuel were chosen. It could be observed that the degree of illumination of porous medium was increased with fuel consumption by focusing at low operation range. Some part of flame propagated within the medium, while another was burned diffusively with secondary air. However, there was significant distinction at 3 L/min of fuel. Flame still propagated within 15ppi medium, but completely burned in stagnant air in case of 20ppi. At the rate beyond 3 L/min, flame lift-off took place on both burners.

The premixed temperature is illustrated in Fig.4 comparing between 15 and 20 ppi of the burners. T1 and T2 were indicated with similar trend between two burners. While, T2 was produced higher in magnitude than those of T1, since the thermocouple of T2 was settled nearer to the combustion zone. Moreover, the temperature profile of both burners could be observed separately into two parts. Within the range of 1-2.5 L/min, it was increased with fuel consumption as the mixtures received the heat from porous media by radiation mode. This also correlated with the degree of illumination. Beyond 2.5 L/min, the temperature was, however, dropped corresponding to the flame lift-off (or nearly lift-off) expressed in Fig.3. By considering at T2, temperature of the low density of pore burner was given significantly higher than the dense one at 3-5 L/min. This revealed that even though the visual flame exhibited lift-off, there was radiated heat transferring back to the thermocouple in the premixed chamber in case of 15 ppi.

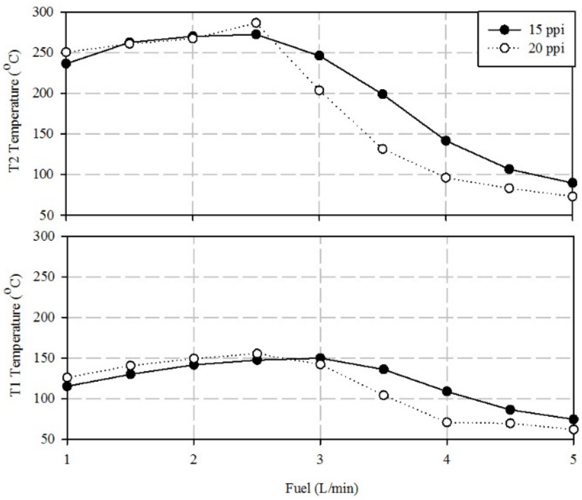


Fig.4 Preheated temperature in a premixed chamber

It was evidently that the results of both flame and temperature performed with stability only within limited range. In the other words, the propagation of flame was taken place within the narrow range of flow. Therefore, as aforesaid in introduction part, the Pe could be used as an important indicator identifying the propagation of flame within porous medium. The relationship in Eq.(1), expresses two main parameters affecting on stability under the same gaseous fuel type, namely d_m and S_L. By concerning structure of porous, d_m for porous foam was described as a mean diameter of ten pores [9] which was 5 and 3.3mm for 15 and 20ppi respectively. However, these diameter sizes were too close to take an effect on Pe variation. Therefore, flame stability in this work would be mainly focused on S_L via considering through percent premixed.

According to the difference of pore size, we expected there was an effect on flow dynamics of mixture and also primary air entrainment. An oxygen concentration in mixing tube was then recorded and calculated to obtain the value of percent premixed. It was seen in Fig.5 that, by equaling total volume of voids, size of pore evidently performed an effect on pressure drop. The large pores could enhance more entrainment of air, while an effect of pressure drop was evident within small pores throughout fuel range. This coincided with Boomsma and Poulikakos's work [10], that with decreasing pore size of porous matrix would come up with increasing flow resistance due to increase on the specific area.

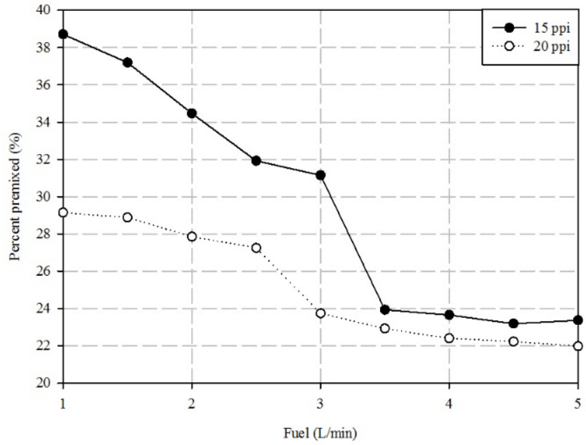


Fig.5 Percent premixed

To achieve correlation with flame stability, an equivalence ratio(Φ) was directly calculated from percent premixed. In this case, the secondary air was neglected due to almost of its entrainment taking place after the combustion in porous media. It was seen from Fig.6 that the results of both burners were located within the range of 2.5-4.5 which was defined as fuel rich condition. These calculated Φ related with low S_L which were proven associated with Pe less than 65. The value lower than this critical value was claimed to come up with unstable flame. Nevertheless, the stable flame result in this work was found at $\Phi < 4$. This obviously indicated that the critical Pe of 65 could not be adopted for rich LPG-air (propane-air) condition. As shown in publication in 2004, Trimis and co-worker indicated the critical Pe relating with Lewis-number (Le) for rich propane-air, approximately, at 28 [7].

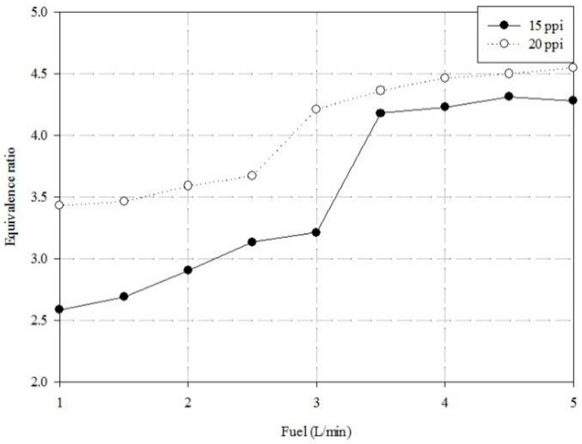


Fig.6 Equivalence ratio

In aspect of the difference of pore density, the 15ppi porous burner promoted greater range of flame stability than the 15ppi porous burner. This could also relate with insufficient S_L, since an effect of pressure drop on 20ppi or small pores caused in blockage of primary air entrainment. Therefore, in case of fuel rich condition of propane-air combustion in porous media, insufficient value of S_L played more significant role on flame stability as comparing with d_m.

4. Conclusion

The flame stabilization of modified premixed LPG burner for ceramics industry with different pore density porous media was investigated. The experiment was conducted on fuel range of 1-5 L/min with self-air entrainment of injector. The porous foams, made of alumina with pore density of 15 and 20 ppi, were constructed in cylindrical geometry and replaced for an iron cast conventional burner. Flame visibility was observed in addition with the gas mixtures temperature profile at different fuel-air mixture ratio prior to combustion.

The results of visible flame and temperature were agreed. The larger pores size alumina, 15ppi, gave wider range of flame stability than small pores medium, thus great recirculating of heat. Since flame stability was depended on sufficient fuel-air ratio, the reduction of pressure drop effect of the big cavity led to greater primary air entrainment.

While the flame lift-off took place on both cases of pore density when $\Phi > 4$, since it correlated with insufficient S_L. This indicated that S_L was strongly played an important role on stability at fuel rich propane-air condition. Moreover, the finding in this work affirmed that the critical of fuel rich propane-air was settle at Pe<65.

5. Acknowledgement

The authors are grateful to the financial support from Thailand Research Fund under a Royal Golden Jubilee Ph.D. Scholarship, jointly funded by King Mongkut's Institute of Technology Ladkrabang.

6. Reference

[1] Laphirattanakul, P. (2012), Mixing and Combustion Improvement by Modified Nozzle on a Premixed LPG Burner, Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang, Thailand.

[2] Laphirattanakul P. and Charoensuk J. (2011), The development of LPG burner in ceramics industry: part 1, paper presented in *The 25th Conference of Mechanical Engineering Network of Thailand*, Krabi, Thailand.

[3] Laphirattanakul, A. and Charoensuk, J. (2011), The study of capable in LPG turn up/down of semi-automatic LPG burner in ceramics industry: part 2, paper presented in *The 25th Conference of Mechanical Engineering Network of Thailand*, Krabi, Thailand.

[4] Laphirattanakul, A., Laphirattanakul, P. and Charoensuk, J. (2012), Comparison of conventional and developed LPG burner operating: fuel jet shape and burner performance, paper presented in *The 26th Conference of Mechanical Engineering Network of Thailand*, Chiangrai, Thailand.

[5] Mujeebu, M.A., Abdullah, M.Z., Abubakar, A.Z., Mohamad, A.A., Abdulah, M.K. (2009), Combustion in porous media and its applications – A comprehensive survey, *Journal of Environmental Management*, March 2009, Vol. 90, pp. 2287-2312.

[6] Wood, S., Harris, A.T. (2008), Porous burners for lean-burner applications, *Progress in Energy and Combustion Science*, June 2008, Vol. 34, pp. 667-684.

[7] Trimis, D and Wawrzinek, K. (2004), Flame stabilization of highly diffusive gas mixtures in porous inert media, *Journal of Computational and Applied Mechanics*, December 2003, Vol. 5(2), pp. 367-381

[8] Gao, H., Qu, Z., Feng, X. and Tao, W. (2014), Combustion of methane/air mixtures in a two-layer porous burner: A comparison of alumina foams, beads and honeycombs, *Experiment Thermal and Fluid Science*, September 2013, Vol. 52, pp. 215-220.

[9] Mach, F.R.A., Issendorff, F.V., Delgado, A. and Ortona, A. (2008), Experimental Investigation of the Oxidation Behavior of SISIC-Foams, *Advances in Bioceramics and Porous Ceramics: Ceramic Engineering and Science Proceedings*, Vol 29(7), pp.229-311.

[10] Boomsma, K. and Poulikakos, D. (2002), The effects of Compression and Pore size Variations on the liquid Flow Characteristics in Metal Foams, *Journal of Fluids Engineering*, March 2002, Vol.124, pp. 263-272.