Down-flow Combustion of Liquid Fuels through Porous Media without Spray Atomization

Sumrerng Jugjai* and Nopporn Polmart

Combustion and Engine Research Laboratory (CERL)
Department of Mechanical Engineering,
King Mongkut's University of Technology Thonburi (KMUTT),
91 Sukswas 48, Bangmod, Tungkru, Bangkok 10140, THAILAND
Tel. (662) 470-9111, 470-9128, Fax. (662) 470-9111
E-mail: sumrueng.jug@kmutt.ac.th

* Author to whom all correspondence should be addressed.

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Abstract : Existing designs of most conventional liquid fuel burners have relied solely on spray atomizers, with a large amount of very fine droplets forming in a relatively large combustion chamber, resulting in a relatively low combustion intensity. Against this background, a novel down-flow compact porous burner system was developed for burning kerosene without the need of using a spray atomizer. Successive development on this burner research is important in view of the need to create energy by an efficient device based on simple technology. The focus has been on the introduction of the packed bed emitter installed downstream of the porous burner. The evaporation process and combustion phenomena that occurred are described through the coupled interaction of the solid phase (porous burner), the liquid phase (kerosene) and the gas phase. Enhancement of evaporation and combustion are evaluated through the measured thermal structures in terms of temperature distribution along the burner length and emission characteristics at the burner exit. Stable combustion with low emission of pollutants was realized even though the combustion flame was confined in-between the porous burner and the packed bed emitter with an increase in the back-pressure. The effects of various parameters including heat input and equivalence ratio on the combustion characteristics were clarified to confirm improvement in mixing of the fuel vapor/air mixture and turn-down ratio of the burner. The effect of the introduced packed bed emitter with suitable bed length and its installation location is investigated as an efficient method for enhancement of evaporation and combustion of the liquid fuel without a spray atomizer. Future applications of this type of burner system are suggested.

Keywords: Down-flow, Liquid fuels combustion, Porous media, Packed bed, Evaporation enhancement, Combustion enhancement, Radiation.

Introduction

Considerable practical benefits from combustion of hydrocarbon fuels within porous inert media (PIM) (for both one way flow combustion [1-5] and for reciprocation flow combustion [6-11]) when compared with conventional open flame burners have been well understood by numerous researchers. Driven by the desire for higher radiant heating rates and the need to emit minimal pollutants, their interest in porous media combustion has been growing. It emphasizes combustion within the PIM, rather than combustion that occurs at the surface of the PIM. During the past decade, emphasis has been placed on the 'gaseous fuel' combustion in the PIM [1-11], wherein the heat transfer phenomena and the combustion regime taking place were well-understood.

While the above-mentioned development of combustion using porous medium technology has been focused on gaseous fuel, very little attention [12-16] has been paid to the combustion of 'liquid fuel'. Existing liquid fuel burners by the PIM have solely relied on the combustion within the PIM with liquid fuel atomizer. The importance of the combustion within the PIM need not be stressed here, owing to its efficient heat recirculation, high combustion intensity and low emission pollutants. However, in view of practical application, it is less attractive owing to its complexity in operation. Thus, improvement in the combustion technique of the liquid fuel by the PIM is of great interest in view of the need for efficient energy creation based on simple technologies and concerns on global environmental pollution.

In the present work, we study the interacting effects of a packed bed emitter installed downstream of the porous burner, in which evaporation of liquid kerosene takes place followed by combustion near the burner surface without the need of using a fuel atomizer or very fine droplets. Liquid kerosene is supplied by droplets (instead of in droplet spray) to the top surface of a horizontal porous burner. The effect of three-way swirling air supply, the bed height of the packed bed emitter, and its installation location on mixing and combustion characteristics are included in the experiment. The experiment and results presented in the previous study [17] excluded these effects and therefore, the present work is considered a more detailed experiment than earlier in studying the coupled changes in the evaporation and the combustion characteristics.

Experimental apparatus and procedure

Figure 1 shows an experimental apparatus of the new version of the porous burner for liquid kerosene combustion. The design concept, size, operational function, experimental apparatus and instrumentation are quite similar to those of the previous one [17] but with a different swirling air supply and down-stream packed bed emitter. The swirling air is equally divided and supplied into the combustion chamber from three directions (see section A-A) instead of from a single swirling air tube as used in the previous studies [17]. The swirling air in each direction is directed towards the center of the combustion chamber at an angle of about 15 degrees in the radial direction and at 10 degrees to the horizontal plane. Therefore, the mixing of the fuel vapor emerging from the porous burner together with the combustion air at the central region of the combustion chamber can be improved, whilst turbulence in the circumference of the chamber is maintained in a stable state (see Figure 2). The downstream packed bed emitter with bed height H is installed at a distance d from the lower surface of the porous burner for studying the effect of the difference of the boundary condition at the chamber outlet on the evaporation and combustion phenomena. The structure of the packed bed emitter consists of a randomly packed bed of 5-mm solid aluminium spheres instead of a stack of pieces of stainless steel wire net as used in the previous study [17]. A U-tube manometer is attached at the upper end of the apparatus to measure pressure P inside the injection chamber.

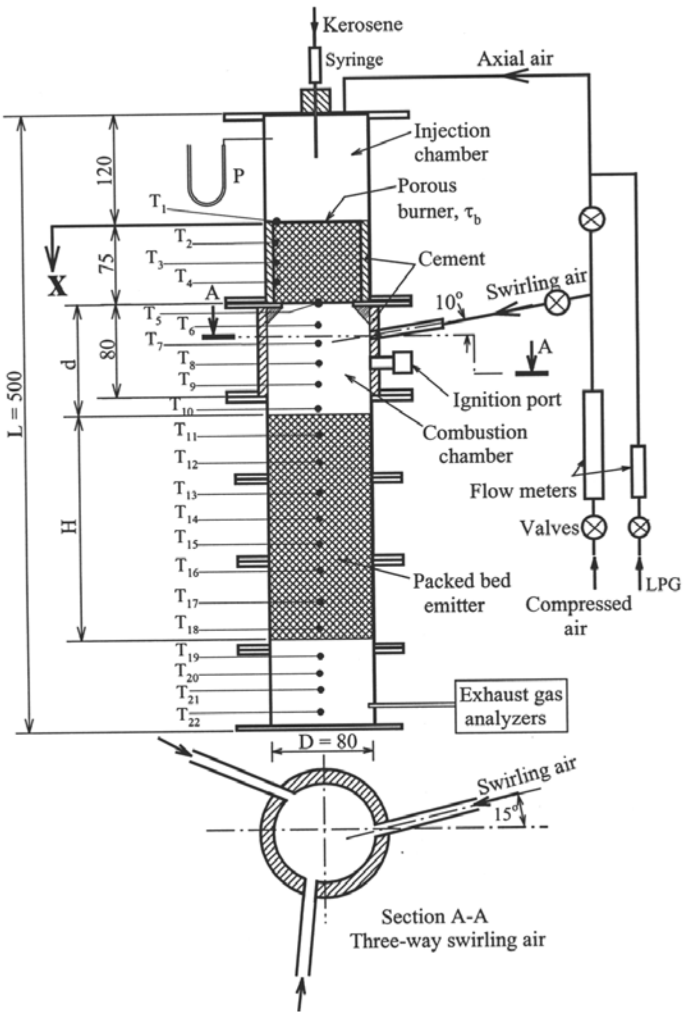

Figure 1. Experimental apparatus with three-way swirling air and packed bed emitter.

The operating procedure of the burner is quite similar to that of the previous study [17]. However, in switching the fuel from the liquefied petroleum gas (LPG) for initial preheating to the liquid kerosene, the axial air is not completely turned-off as was done in the previous study [17]. A small amount of the axial air is required just for balancing the pressure exerting at both ends of the porous burner, in which a layer of liquid kerosene is embedded. This liquid layer serves as a liquid seal that may be moved up as combustion takes place due to an increase in pressure. This movement is further enhanced in the case of combustion with the porous emitter installed owing to increase in back-pressure. This causes interruption of the fuel supply because, in this experiment, the fuel is supplied by droplets to the porous burner by gravitational force.

Results

Combustion flame, mixing, evaporation followed by combustion phenomena

In as much as the concept in the combustion of liquid fuel using a porous medium without atomization is attractive from the point of view of an efficient device for energy creation based on simple technology, the experiment on combustion without the packed bed emitter is carried out first to demonstrate improvement in mixing and to understand the mechanism of evaporation followed by combustion phenomena. Figure 2 shows a typical steady state luminous turbulent flame with the three-way swirling air at CL = 6.65 kW and $\Phi = 0.86$.

With this swirling air supply, the combustion flame near the lower

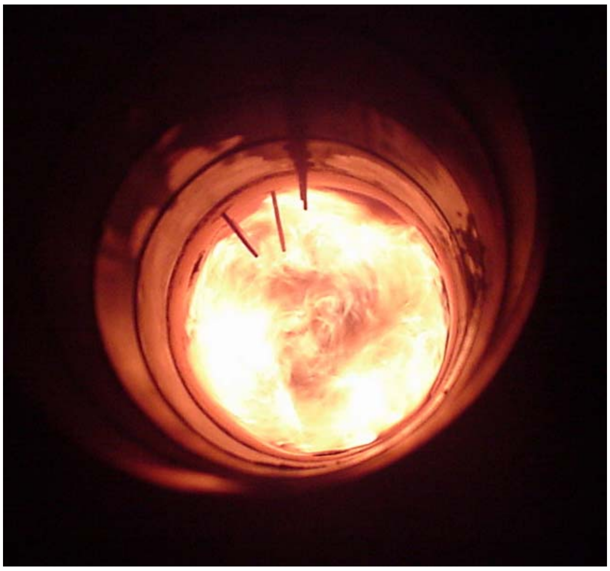

Figure 2. Typical combustion flame with three-way swirling air. (CL = 6.65 kW, Φ = 0.86).

surface of the porous burner behaves like a homogeneous premixed flame and occurs almost throughout the cross section area of the combustor under complex flow pattern (i.e. highly turbulent flow created by swirling flow and impinging flow between jets) rather than simple swirling flow along the circumference of the combustor wall as observed with a single swirling air tube in the previous study [17]. The fuel rich zone at the centre of the cross section area of the combustor is minimized when compared with that of the single swirling air as shown in Figure 3, resulting in a more complete combustion without soot and odor as observed in the previous study [17]. Since so many phenomena are involved within the porous burner and the combustion chamber, the most probable evaporation and combustion mechanism is shown in Figure 4. Liquid fuel vaporizes

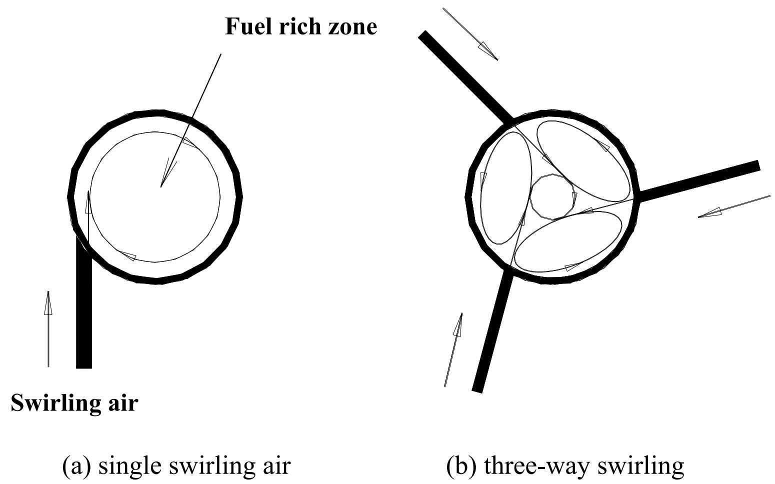

Figure 3. Comparison of swirling flow pattern.

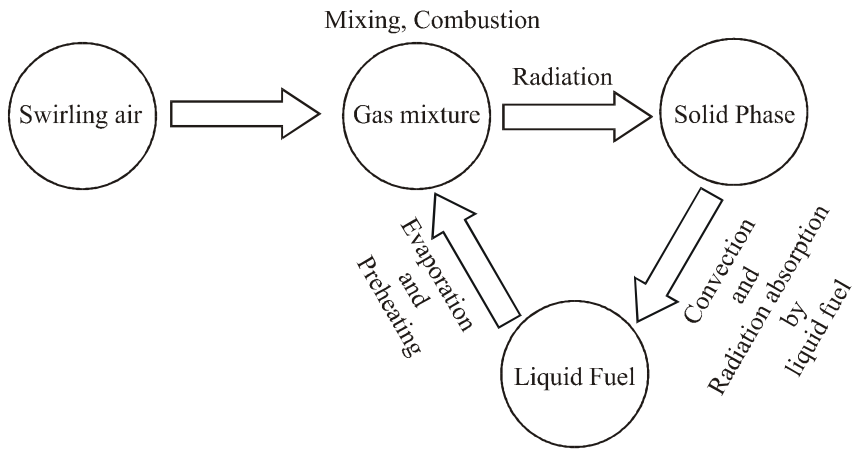

Figure 4. Evaporation and combustion mechanism.

within the solid phase (porous burner), wherein the liquid fuel is supplied. Evaporation of the liquid fuel and preheating of the fuel vapor inside the solid phase require latent heat and sensible heat, which are supported by convective heat transfer from solid to liquid/vapor via solid-liquid/vapor interactions and by thermal radiation absorption by the liquid fuel and the fuel vapor. Chemical reaction takes place outside the porous burner near its lower surface, where the preheated liquid fuel vapor meets and mixes with the swirling air supplied from the sidewall of the combustion chamber to form a homogeneous gas mixture followed by combustion. Thermal radiation from flame is involved by the solid phase (porous burner) to create an energy feed-back mechanism, which in turn creates evaporation. This evaporation followed by combustion phenomena occurs continuously so long as the liquid fuel and the swirling air are continuously supplied to the porous burner system.

Effect of heat input CL

Heat input CL was increased as high as possible to investigate the turn-down ratio of this burner system provided the maximum temperature occurred does not exceed the limitation of the thermocouples used (1300^{o}C). Figure 5 shows the effect of the CL on temperature distributions along the length of the burner at Φ = 0.86 and H = 0 (i.e. without the packed bed emitter). Increasing CL from

6.65 to 13.49 kW at constant Φ = 0.86 yields a further increase in the temperature levels almost entirely throughout the burner length.

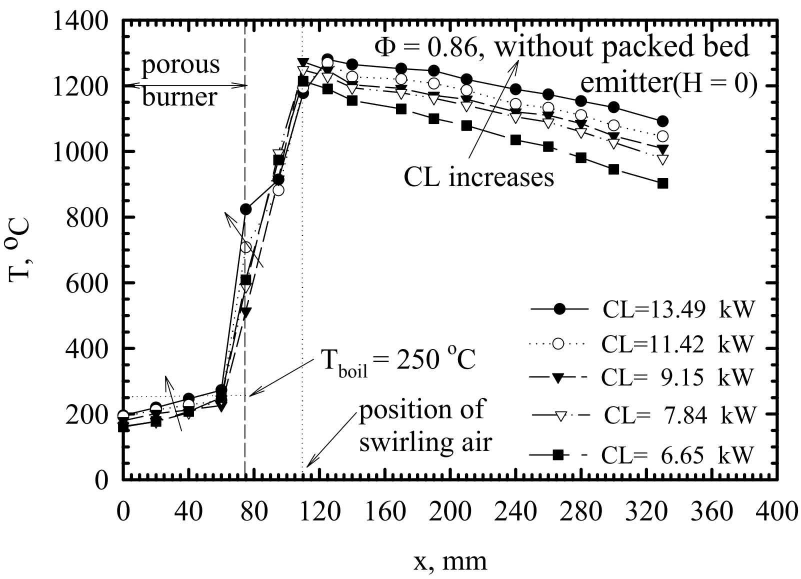

Figure 5. Effect of CL (without packed bed emitter (H = 0)).

Further increase in CL is not possible due to excessive maximum temperature. Focuses have been made on special features obtained from this combustion system; complete evaporation within the porous burner with the value of T_5 being much higher than boiling temperature (T_{boil} = 250 ^oC) and Leidenfrost temperature [18], efficient preheating effect of the fuel vapor enabling auto-ignition, temperature profile behaving like a conventional gaseous premixed flame with steep temperature gradient and so on, remain the same as those in the previous study [17]. The higher the CL is, the higher the temperatures of the porous burner become (especially T_5), thus enhancing the evaporation of the kerosene fuel with efficient preheating of the fuel vapor within the porous burner. This is attributed to a strong energy feedback mechanism by thermal radiation from flame and the combustion chamber wall toward the porous burner. Even though the increase in CL is also proportional to the increase in the gas flow velocity, the location of the flame zone defined as the location of the maximum temperature measured (T_7 or T_8) is not likely to be shifted downstream from the location of the swirling air. This is attributed to the dominating energy feedback mechanism by thermal radiation to the porous burner, where evaporation and vapor preheating followed by combustion can be further enhanced as CL increases. Highly turbulent flow obtained in this study also contributes to this flame stabilization. Thermal structures deep inside the porous burner (T_1 to T_4) are slightly increased with CL owing to sufficiently large optical thickness of the porous burner (τ_b = 30). Figure 6 shows the corresponding CO and NO_X emissions. Available emission characteristics [14, 17] were included for comparison, though they are obtained at different range of CL with different Φ from those in the

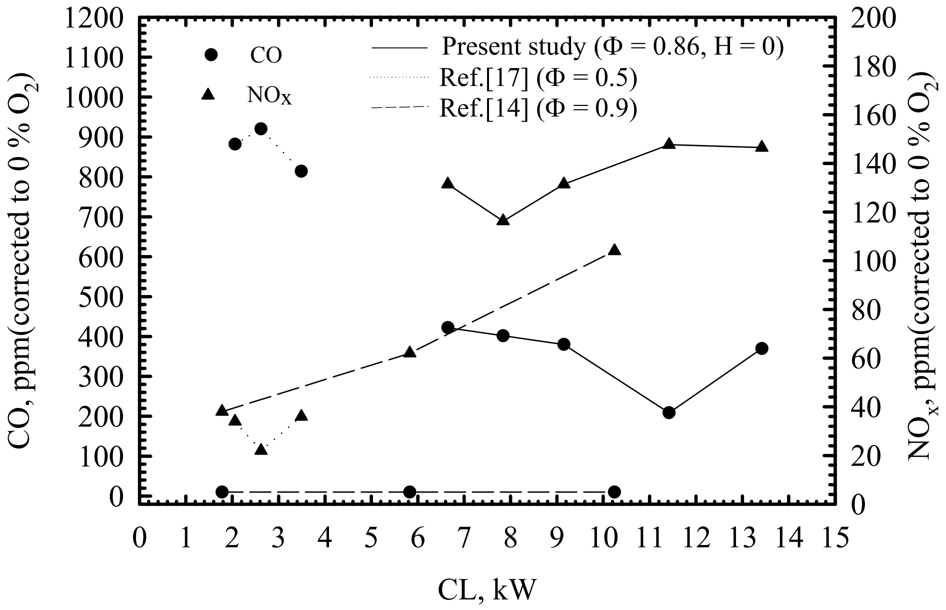

Figure 6. Effect of CL on CO and NO_X.

present study. The same trend of decrease in CO, while an increase in NO_x emission with an increase in CL is observed for every study, especially, in the present study and Takami et al. [14]. Emission levels of CO and NO_X for the present study are similar to those found by Takami et al. [14] but quite different from those of the previous study [17]. CO emission in the present study is relatively low compared with that of the previous study [17] because of improvement in mixing and a more complete combustion at higher combustion temperature. NO_X emission of lower than 160 ppm was observed for every run in the present study and was slightly higher than that of [17], because of higher temperature levels at higher CL.

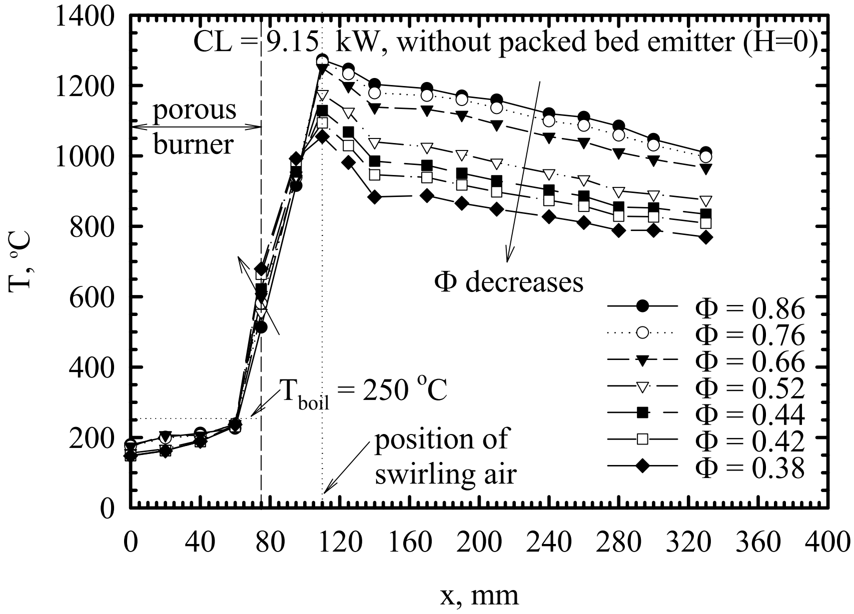

Figure 7. Effect of Φ. (H = 0).

Effect of equivalence ratio Φ

Figure 7 shows the effect of the equivalence ratio Φ on the thermal structure in terms of the temperature distributions along the axis of the burner at CL = 9.15 kW and H = 0. When Φ was decreased from 0.86 to 0.38 by increasing the swirling air flow rate, the temperature profiles from the position of the swirling air (at x = 110 mm) to the burner downstream were markedly decreased, whereas those inside of the porous burner were almost unchanged except for T_5

and T_6 increasing. This increase is attributed to the improvement in mixing between the fuel vapor and the swirling air supplied at higher airflow rate, resulting in flame movement toward the lower surface of the porous burner.

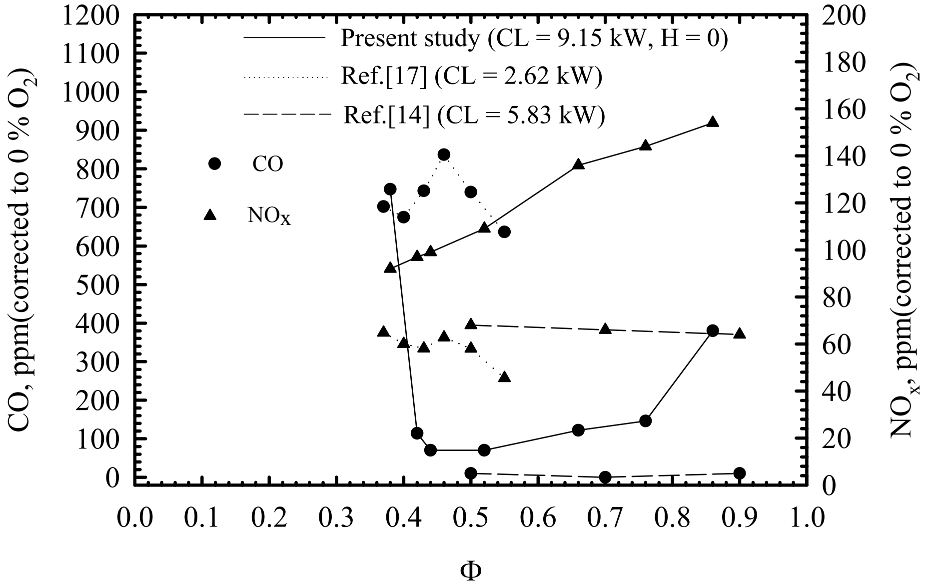

Figure 8. Effect of Φ on CO and NO_X.

Figure 8 shows the effect of Φ on the CO and the NO_X emissions. Available emission characteristics [14, 17] were also included for comparison, but they are obtained at a different range of Φ at different CL from those appearing in the present study. With the equivalence ratio in the range $0.4 < \Phi < 0.76$, the CO concentration of the present study is relatively low and almost unchanged, evidencing the same trend as that of Takami et al. [14]. Out of this range, the present study shows a trend of steep increase in CO emission due to incomplete combustion. Emission levels of NO_X for the present study are twice as high as those found by Takami et al. [14], but this is relatively small in absolute values. The contrast in CO emissions between the present study and the previous one [17] is remarkable. The present study shows significantly lower CO emissions, and slightly higher NO_x concentration than those of the previous study [17], confirming improvement in mixing and a more complete combustion at higher temperature level.

Combustion enhancement by the packed bed emitter and effect of its bed height H

Figure 9 compares the temperature profiles along the length of the burner for the system with and without the packed bed emitter (H = 0) at CL = 9.15 kW, Φ = 0.37 and d = 80 mm.

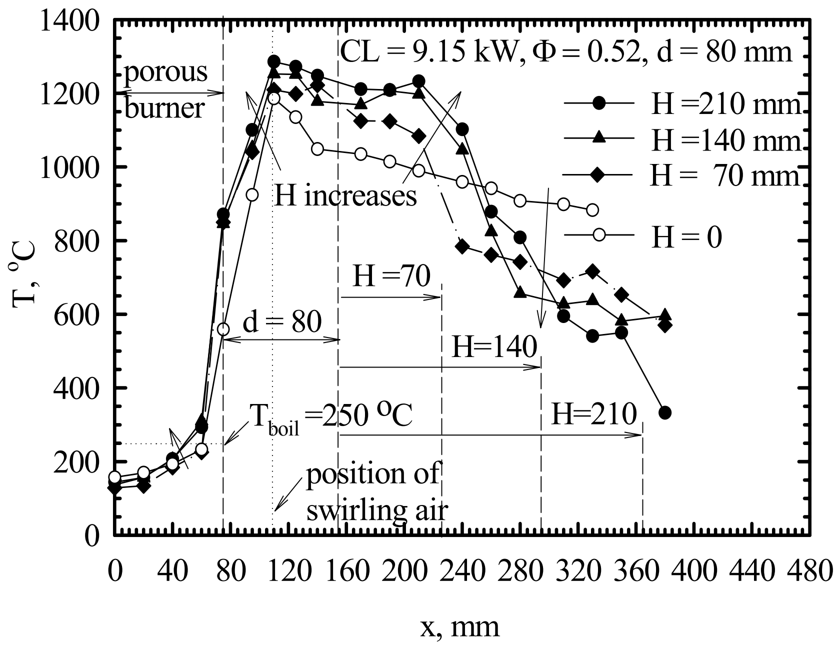

Figure 9. Enhancement of evaporation and combustion by a packed bed emitter and effect of its height, H.

Also variation of the bed height H of the packed bed emitter at H = 70 mm, H = 140 mm and H 210 mm are included to further study the coupled changes in the evaporation and the combustion phenomena. The results reveal that significant improvement in both evaporation and combustion processes can be achieved by installing the packed bed emitter downstream. The emitter with H = 70 mm yields higher temperatures within both the combustion chamber (especially, T_6 to T_9) and the emitter (T_{10} to T_{12}) but lower exhaust gas temperature at the emitter exit (at x = 240 mm) than the case without the emitter

(H = 0). This result can be expected in view of the additional energy feedback provided by the thermal radiation emitted from the emitter to the porous burner [2] and thermal radiation shield provided by the emitter. The higher the bed height H is, the higher and the more uniform the combustion temperatures (especially, T_6 to T_{12}) become, thus enhancing the combustion process. However, the temperatures within the porous burner (T_1 to T_5) were almost unchanged as H increases. This means no further improvement in evaporation process within the porous burner. This may be attributed to change in the combustion regime. The turbulent combustion which mainly takes place in free space in the case without the porous emitter (H = 0) was shifted to a combustion which partially takes place within both the free space ($75 \leq x \leq 155$) and the packed bed emitter with the existence of flue gas re-circulation resulting from increase in back-pressure. Thus, radiative heat flux emitted from the packed bed emitter toward the porous burner may not significantly improve as H increases due to thermal radiation blockage of the emitter in which the combustion is taking place. This can lead to a constant evaporation rate as observed by almost constant T_3, T_4 and T_5. The emission pollutants (NO_x and CO) and the pressure P were found to have an increasing trend as the bed height H increases as shown in Figs. 10 and 11, respectively. High H leads to high pressure P due to high friction posed by the flow.

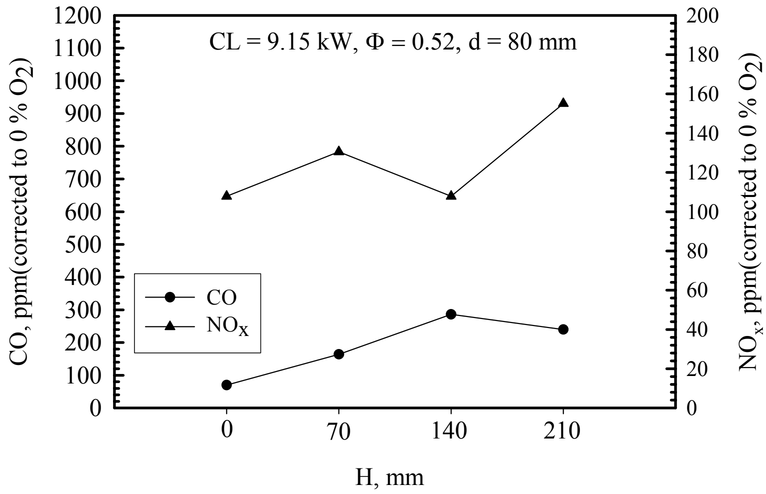

Figure 10. Effect of H on CO and NO_X.

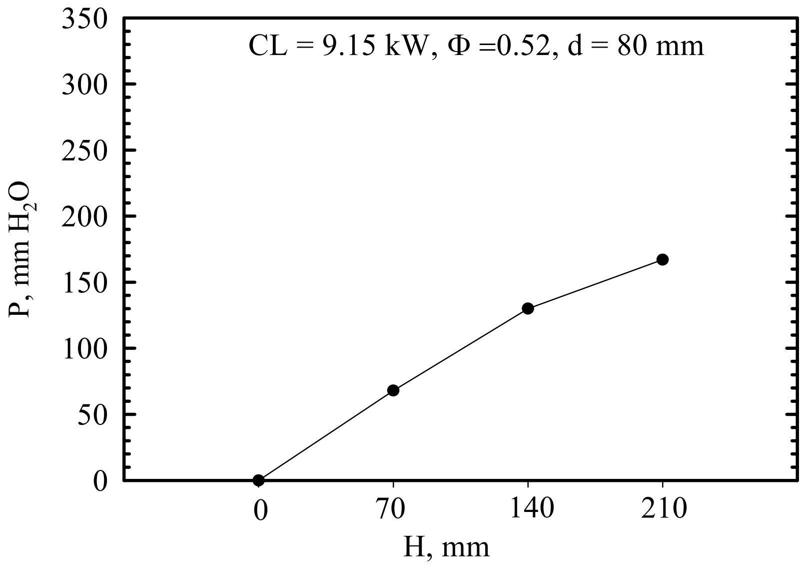

Figure 11. Effect of H on P.

It is important to note that the CO experiences an increasing trend in its concentration as H increases. This behavior may be in contradiction to the increasing temperatures and gives no supporting reasons how the porous burner achieved higher combustion temperature, while achieving incomplete combustion at the same time. One possible reason may be accumulation of the CO emissions as H increases. Installation of the packed bed emitter causes back-pressure and dissipation of turbulence of the combustion gas, thus leading to poor ventilation from the combustion chamber, while combustion is enhanced by change in the combustion regime from combustion in free space to combustion within the packed bed emitter. It can be expected that once the pressure P is above a limited value, the CO concentration continues to increase, whereas the temperature falls until reaction ceases and the whole combustion process is stopped. Thus, further increase in the bed height H of more than 210 mm was not performed in this experiment.

Effect of inter distance d between the porous burner and the packed bed emitter

The effect of d on temperature distributions along the burner axis is shown in Figure 12 for CL = 9.15 kW, Φ = 0.52 and H = 70 mm. The temperature profile for the system without the packed bed emitter (H = 0) is also included for comparison. It is evident from Figure 12 that the distance d significantly affects the fuel vapor preheating rather than evaporation and combustion characteristics.

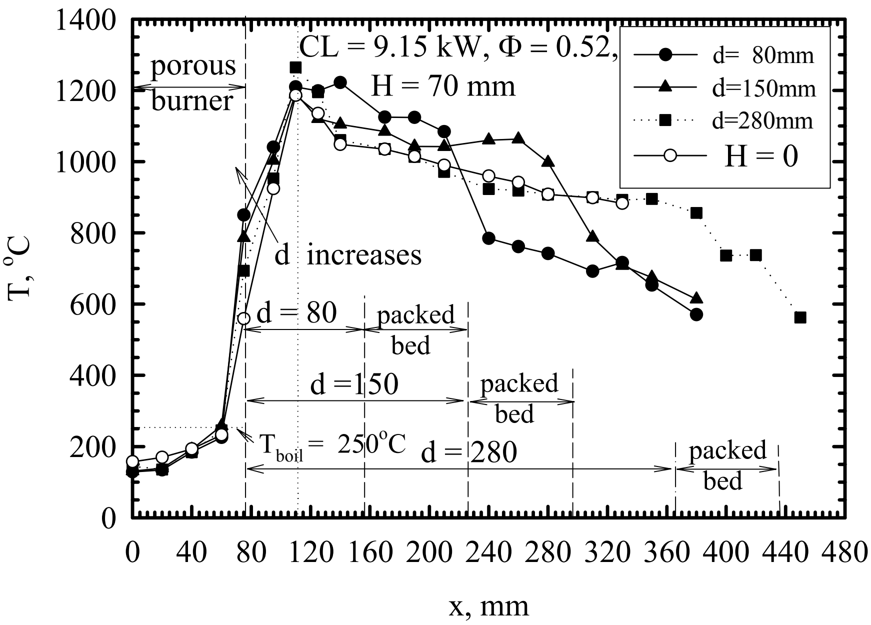

Figure 12. Effect of d.

Only the lower surface of the porous burner (T_5) was significantly improved, while the temperatures deep inside the porous burner (T_1, T_2, T_3 and T_4) and maximum combustion temperature (T_7) are almost unchanged as d varied. The improvement in T_5 is due mainly to improvement in shape factor as the distance d decreases. Nevertheless, the CO and NO_x emissions are almost independent of d as shown in Figure 13. Also the emissions for the system with H = 0 were included for comparison. Again, with the packed bed emitter installed, the emission level is slightly higher as compared with the system with H = 0 due to an increase in the back-pressure P as shown in Figure 14. Thus, it is recommended that the packed bed porous emitter be installed as near as possible to the porous burner, so stable and complete combustion at relatively high temperature level is maintained.

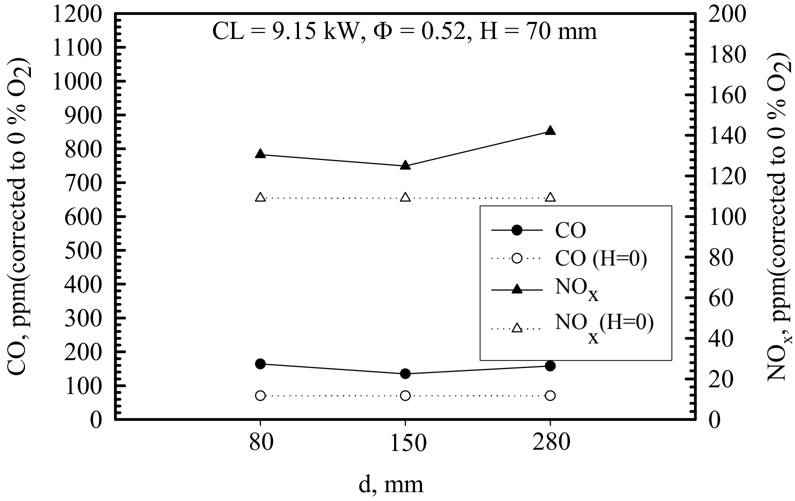

Figure 13. Effect of d on CO and NO_X.

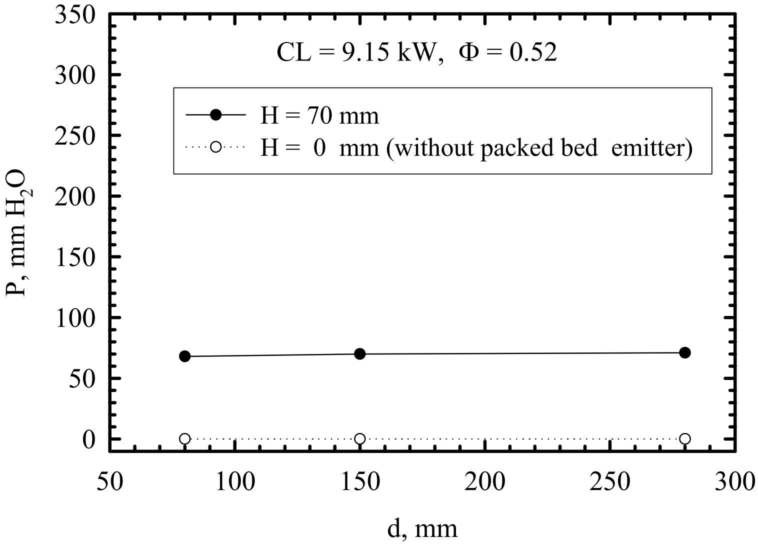

Figure 14. Effect of d on P.

Flammability region of the porous burner

Figure 15 shows the flame stability diagram as a function of the heat input CL and the equivalence ratio Φ at the typical value of H = 140 mm and d = 80 mm. It can be seen that stable combustion conditions at an equivalence ratio as small as 0.2 are remarkable. It now became possible to burn stably the liquid kerosene as lean as

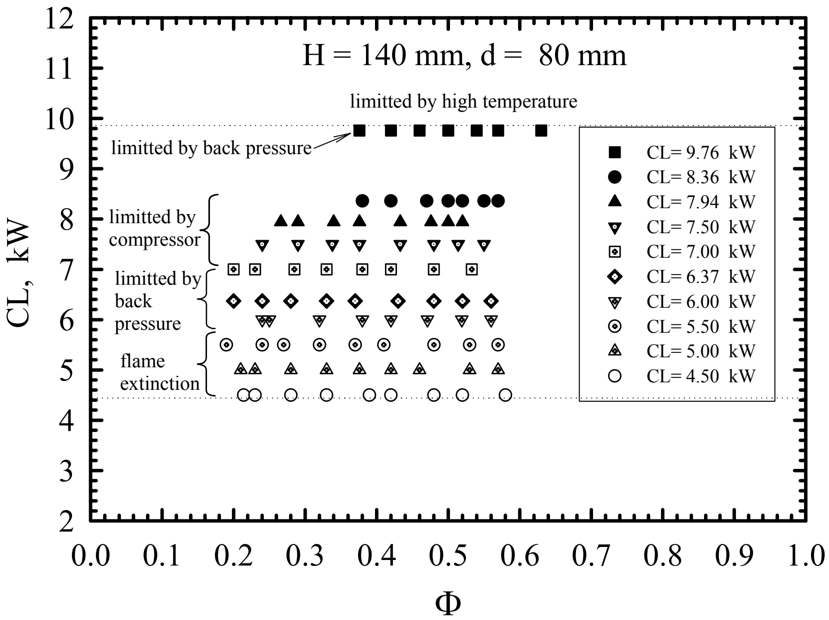

Figure 15. Flammability region.

Φ = 0.2 at which the flame extinction limit was reached at relatively low CL = 4.5-5.5 kW by this porous burner. However, at a relatively high CL, which requires a larger amount of combustion air, stable combustion cannot be maintained at relatively low Φ, owing to the interruption in fuel flow rate caused by an increase in the back-pressure P. This behavior seemed to be normal for fuel, which is forced to flow by gravitational force. With a further increase in heat input (up to CL = 10 kW) it is also possible to obtain stable combustion, except for relatively low Φ, which is limited by either the insufficient capacity of the compressor used or the excessive high back-pressure P depending on which one occurred first. Experimentation at CL beyond 10 kW was not performed due to a sudden stop in the fuel flow. It was recommended that P should be less than 200 mm H_2O to obtain stable combustion with this combustion system.

Practical usefulness/significance

Applications of this combustion technique are quite new and have had a strong impact on industrial application. These may range from stationary incinerators for liquid hazardous wastes to a new version of a diesel engine used in automobiles [16] and more advanced combustion systems for industrial application to replace the conventional spray burner. These are:

1. Radiant tube burner for burning liquid fuel. Thermal radiation emitted from the external surface of the packed bed emitter can be considered as a significant part of thermal loading. This can be applied as a heat source for newly designed boilers, steam-methanol reformers and more advanced thermal systems such as

thermal fluid heaters for industrial applications. In the residential and commercial areas, this concept may find application in the development of a highly compact, efficient air heater.

2. A simple incinerator without using any kind of conventional atomizer for incinerating hazardous liquid wastes.
3. Industrial burners for use in areas where liquefied petroleum gas or natural gas is not available or where a liquid fuel is a by-product of an industrial/agricultural process.

Conclusions

Successive development on down-flow combustion of kerosene fuel using porous media without the need for liquid atomization has been carried out. Improvement in mixing of vapor/air, the evaporation mechanism and combustion characteristics were realized through the implementation of a newly designed three-way swirling air system and the installation of the packed bed emitter. The effect of the main parameters on burner performance has been investigated to this end. The following conclusions can be drawn from the experimental results:

1. The mixing process between the fuel vapor and the swirling air can be greatly improved throughout the cross section of the burner by using the newly designed three-way swirling air system. Very strong turbulence combustion can be obtained through swirling flow and impinging flow between jets supplied by the three-way

swirling air, resulting in a more complete combustion at higher heat input rate when compared with the single swirling air tube as used in the pervious study [17].

2. It has been revealed that turbulent flame could be stabilized in the combustion chamber, even though the flame is confined by the packed bed emitter and the porous burner with an increase in the back-pressure. The packed bed emitter plays a very important role in enhancing evaporation and combustion characteristics with more uniform temperature profiles in the combustor when compared with the conventional system without the porous emitter installed. Most of the enthalpy of the combustion gas is converted to thermal radiation by the packed bed emitter; a significant part of thermal loading for industrial applications. The pollution emission characteristics were quite good, while the back-pressure or pumping loss due to forcing the gas flow through the packed bed emitter remained within tolerable ranges.

3. The effect of the heat input, equivalence ratio, packed bed emitter, height of the packed bed and its installation location in relation to the porous burner on temperature distribution, evaporation and combustion characteristics was elucidated. Relatively low NO_X emission was observed for the whole operating range under investigation. CO emissions were found to be strongly dependent on the operating conditions and bed length of the packed bed emitter used.

4. Finally, it can be stated that the present experiment further shows that the porous burner equipped with the porous emitter investigated here is an efficient device to create clean energy based on simple technologies.

Recommendation and future research needs

Much work remains to be done to further investigate combustion phenomena and heat transfer characteristics within the new version of the porous medium burner for liquid fuels. In particular, a better understanding is needed of the combustion regime with regard to existence of the packed bed emitter and its radiative properties and physical properties. This method of heat utilization is of interest in engineering applications and needs to be examined further, as well as the ability of the burner to be scaled-up in capacity and operated in other burner orientations. Theoretical study is also worth undertaking to more fully understand the complex phenomena of heat and mass transfer, phase change and chemical kinetics which simultaneously took place inside the system.

Nomenclature

CL Heat input, kW

D Diameter, mm

d Inter distance between the porous burner and the packed bed emitter, mm

H Bed height of the packed bed emitter, mm

L Length, mm

P Pressure, mm H_2O

T Temperature, ^{o}C

x Distance, mm

Greek symbols

Φ Equivalence ratio (ratio of theoretical air to practical air supplied)

τ Optical thickness (a measure of the ability of a medium to attenuate energy and is equal to the extinction coefficient (having unit in length^{-1}) integrated over the path length)

Subscripts

b Burner

boil Boiling

References

[1] Takeno T. and Sato K. (1979) An excess enthalpy flame theory, *Combust. Sci. and Technol.*, 20, 73-84.

[2] Yoshizawa Y., Sasaki K. and Echigo R. (1988) Analytical study of the structure of radiation controlled flame, *Int. J. Heat Mass Transfer*, 31 (2), 311-319.

[3] Sath S.B., Peck R.E. and Tong T.W. (1990) A numerical analysis of heat transfer and combustion in porous radiant burners, *Int. J. Heat Mass Transfer,* 33 (6), 1331-1338.

[4] Howell J.R., Hall M.J. and Ellzey J.L. (1996) Combustion of hydrocarbon fuels within porous inert media, *Prog. Energy Combust. Sci.*, 22, 121-145.

[5] Oliveira A.A.M. and Kaviany M. (2001) Nonequilibrium in the transport of heat and reactants in combustion in porous media, *Prog. Energy Combust. Sci.*, 27, 523-545.

[6] Hanamura K., Echigo R. and Zhdanok S. A. (1993) Superadiabatic combustion in a porous medium, *Int. J. Heat Mass Transfer*, 36 (13), 3201-3209.

[7] Hoffmann J. G., Echigo R., Tada S. and Yoshida H. (1995) Analytical study on flammable limits of reciprocating superadiabatic combustion in porous media, *Proceedings of the 8th International Symposium on Transport Phenomena in Combustion*, San Francisco, CA, 2, 1430-1440.

[8] Hoffmann J.G., Echigo R., Yoshida H. and Tada S. (1997) Experimental study on combustion in porous media with a reciprocating flow system, *Combust. Flame,* 111, 2-46.

[9] Jugjai S. and Somjetlertcharoen A. (1999) Multimode heat transfer in cyclic flow reversal combustion in a porous medium, *Int. J. Energy Res*., 23, 183-206.

[10] Jugjai S. (2001) Experimental study on cyclic flow reversal combustion in a porous medium, *Combust. Sci. and Technol.*, 163, 245-260.

[11] Jugjai S., Wongveera S., Teawchaiitiporn T. and Limbwornsin K. (2001) The surface combustor-heater with cyclic flow reversal combustion, *Exp. Therm. Fluid Sci.*, 25(3-4), 183-192.

[12] Kaplan M. and Hall M.J. (1995) The combustion of liquid fuels within a porous media radiant burner, *Exp. Therm. Fluid Sci*. 11 (1), 13-20.

[13] Tseng C.-J. and Howell J.R (1996) Combustion of liquid fuels in porous radiant burner, *Combust. Sci. and Technol.*, 112, 141-161.

[14] Takami H., Suzuki T. (1998) Itaya Y. and Hasatani M., Performance of flammability of kerosene and NO_x emission in the porous burner, *Fuel,* 77 (3), 165-171.

[15] Martynenko V.V. (1998) Echigo R. and Yoshida H., Mathematical model of self-sustaining combustion in inert porous medium with phase change under complex heat transfer, *Int. J. Heat Mass Transfer,* 41 (1), 117-126.

[16] Park C.-W. and Kaviany M. (2002) Evaporation-combustion affected by in-cylinder reciprocating porous regenerator, *ASME J. Heat Transfer*, 124, 184-194.

[17] Jugjai S., Wongpanit N., Laoketkan T. and Nokkaew S. (2002) Experimental Study on Combustion of Liquid Fuels by a Porous Medium, *Exp. Therm. Fluid Sci*., 26(1), 15-23.

[18] Bernardin J.D. and Mudarwar I. (1997) Film boiling heat transfer of droplet streams and sprays, *Int. J. Heat Mass Transfer*, 40, 2579-2593.