Research and Development of a Porous Combustor Heater (PCH) with Cyclic Flow Reversal Combustion (CFRC)

Sumrerng Jugjai*, Viriya Nungniyom

Combustion and Engine Research Laboratory (CERL),
Mechanical Engineering Department, Faculty of Engineering, King Mongkut's University of Technology Thonburi (KMUTT), Bangkok, 10140, Thailand,
Tel: 0-66470-9128, Fax: 0-66470-9111, *E-mail: sumrueng.jug@kmutt.ac.th

Abstract

A new porous combustor-heater (PCH) equipped with a cyclic flow reversal combustion (CFRC) was extensively explored. Effect of a switching period (t_{hp}) ranging from 30 to 390s was investigated to understand flame-surface interaction (quenching effect) and its effect on thermal efficiency and emissions characteristics of the combustor. The new PCH gives two-peak flame temperature alternately occurred at the ends of the combustor, yielding relatively high cycle-averaged temperature over the tube bank and thus enhanced thermal efficiency with low emissions of pollutants (CO and NO_X). Despite relatively long switching period (t_{hp}) of 390s, flame never move into the tube bank and stabilized all the time at the upstream side of the tube bank, implying a strong quenching effect provided by the relatively small pitch distance used in the experiment. This new PCH concept can provide the basis for development of state-of-the-art technology for new versions and more advanced thermal systems, such as highly efficient ultra-low-pollutant-emission boilers, for efficient utilization of energy.

Keywords: Porous combustor-heater (PCH), cyclic flow reversal combustion (CFRC), porous inert medium (PIM)

1. Introduction

Porous combustor-heater (PCH) is a combustion heat transfer device involving relatively cold heat exchange surfaces (or tubes) embedded in a stationary bed of porous inert material (PIM) in which a gaseous fuel is burned. [1]. Unlike the conventional combustor composed of a heat exchanger heated by hot combustion gas, the PCH can provide heat transfer simultaneously with the combustion process in such a way that the temperature distribution in the PCH can be controlled to minimize total emissions. In previous works [1], emphasis was placed on the PCH equipped with conventional one-way flow combustion (hereafter referred to as OWFC), wherein the heat transfer phenomena and the combustion regime taking place were clarified.

A more sophisticated technology of PCH equipped with the state-of-the-art technology of super adiabatic combustion, (hereafter referred to as cyclic flow reversal combustion CFRC) has been recently proposed [2]. The new PCH concept is operated in a forced periodic mode by periodically switching the direction of the inlet flow. Preliminary study is done and the results were evaluated. The most notable advantages of the new PCH with CFRC is that it can yield almost twice as much thermal efficiency as with the conventional OWFC with a much lower CO and NO_X emission (as low as 30 ppm). Furthermore, at some certain experimental condition, it can provide the hot zone that coincided with the embedded tube bank near the center of the reactor despite the strong quenching effect. This phenomenon is very important in view of combustion and heat transfer. The combustion temperature can be significantly reduced because heat is removed simultaneously with the combustion process, and thus formation of nitrogen oxides is suppressed. Heat transfer to the tube bank can be greatly enhanced by thermal radiation form the solid porous matrix and unsteady-state operation of the heat transfer system.

In our previous experimental study [2], however, operating

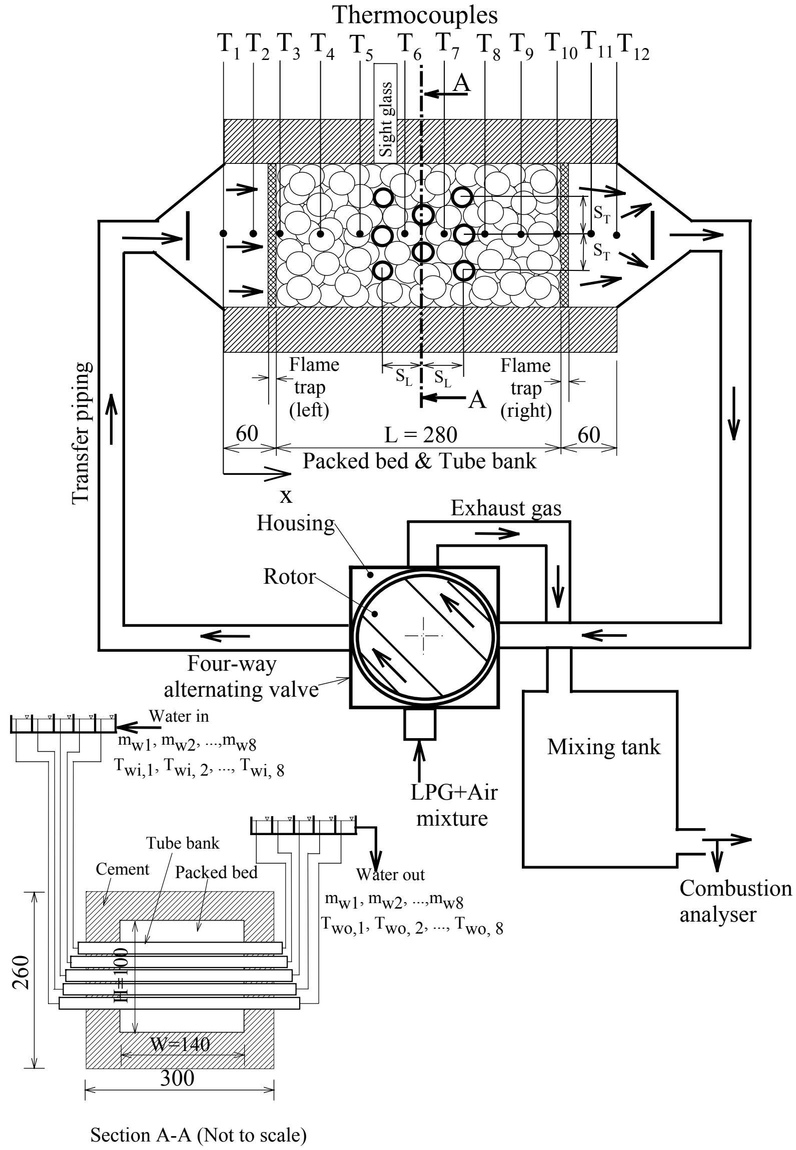

Fig. 1. PCH with CFRC.

ranges of the switching period (t_{hp}) was not large enough to understand flame-surface interaction (quenching effect) and its effect on thermal performance and emission characteristics of the PCH equipped with the CFRC. To clarify this quenching effect and to broaden the base for future research, this experimental study was carried out.

This paper studies in detail aspects of the operating range of switching period (t_{hp}) and their optimization so as to obtain better understanding in this particular combustion phenomenon and maximum possible performance. The switching period t_{hp} was varied within a wider range from 30 to 390 s instead of a narrow one of 10 to 45 s as in the previous one [2].

2. Experiments

2.1 Experimental reactor

The PCH equipped with CFRC has been reported [2]. This design is illustrated in Fig. 1. The system is comprised of a packed bed embedded with a three-row staggered tube bank at the center to remove heat. A four-way, alternating valve and associated transfer piping allow for either forward flow or backward flow operating modes. Premixed combustible gases are produced by injecting liquefied petroleum gas (LPG) into the air stream prior to entering the alternating valve. The exhaust gases, of which their emission level was varied with time when operating the CFRC, are directed to a large mixing tank to stabilize the emission level before measuring.

The PCH with CFRC test unit has a 260 × 300 mm square configuration with a high-temperature insulating block 80 mm thick to minimize heat loss. The chamber is filled with a randomly packed bed of spherical alumina pellets. A cross-flow heat exchanger with a three-row staggered tube bank is embedded in the packed bed to serve as a thermal load. Water was selected as the working fluid of the heat exchanger. In addition, two water-cooled flame traps as shown in Fig. 2 are also embedded in the terminal sections of the test unit to assure nearly ambient-temperature boundary conditions, and serve as thermal loads. The flame traps were specially designed in such a way that the terminal boundaries of the test unit are evenly cooled while a uniformly distributed flow pattern over the cross section of the reactor is maintained. The flame traps can help to minimize the risk of flashback and thus allow the combustion zone to propagate freely in either upstream or downstream directions within the packed bed. The flame trap can also help to minimize radiative heat loss at both terminal sections of the reactor.

2.2 Control system and measurement

Liquefied petroleum gas (LPG) (60% propane, 40% butane; lower heating value: 115 MJ/m^3) and combustion airflow rates are controlled by valves mounted on the control panel (not shown). The fuel gas and the airflow rates are measured by calibrated rotameters. The flow direction of the premixed combustible gas is controlled by the alternating valve, which is alternately rotated by an external driving device (not shown) comprised of a pneumatic cylinder, a connecting rod mechanism, a solenoid valve, a time switch and a limit switch. This allows for periodic change of the flow direction of the combustible mixture. A forward flow (FW) is defined as a clockwise flow direction of the gas through the transfer piping, while a counter-clockwise flow direction is for the backward flow (BW). The switching period for each flow direction can be independently adjusted by a time switch.

The combustion characteristics are determined from profiles of the temperature along the reactor axis and the composition of the combustion gases. In order to know the temperature profiles, B-type sheath thermocouples of T_1 to T_{12} of wire diameter 0.5 mm were used. They are placed equidistantly along the centerline of the reactor. Their signals are digitized by a general-purpose DT 605 Data Logger, and then transmitted to a personal computer. The thermocouple readings can represent the solid phase (or porous medium) temperature since the thermocouples are also solid by themselves. This simplifies the analysis greatly,

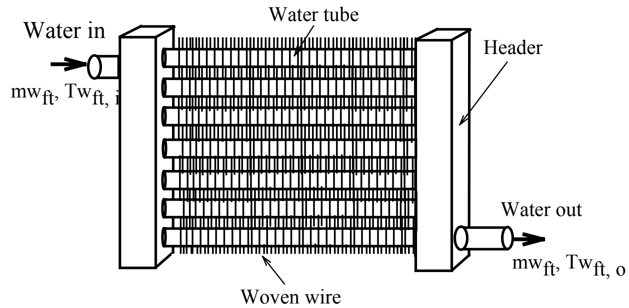

Fig. 2. Flame trap.

and the price we pay for this convenience is some loss in accuracy due to error arising from several effects, such as heat transfer effects caused by conduction and radiation etc. In order to know the true gas temperatures, the thermocouple readings have to be corrected but this was not performed because radiation error involves many unknown due to the complex radiative field around the bead particularly when the thermocouple is inside the porous matrix. Moreover, the uncertainty in the results is high due primarily to the lack of reliable interface convective heat transfer coefficient and also the lack of reliable data for thermophysical/chemical and radiative properties of a porous matrix.

Uncertainties in the intrusive thermocouple measurement are of concern. However, thermocouple is the only technique available at present to measure temperature inside a porous medium burner. Repeated measurement shows an uncertainty of about 10% for the temperature. The results of the measurement are instructive, but should be interpreted with proper caution regarding the limitations of the experimental technique. Upon quasi-steady state condition of CFRC was reached, thermocouple reading for each location was fluctuating with time with almost constant amplitude. Then the temperatures were averaged over the switching period and plotted on a graph.

A spillover water supply system was used to make sure that the water is fully flowing through the cross sectional area of every tube of the heat exchanger. Water flow rate for each tube can be independently controlled, but an equal flow rate for each tube was used throughout the experiment. Also an equal water flow rate for each flame trap was used throughout the experiment. K-type sheath thermocouples independently measured the inlet and outlet temperature of water for each water tube and flame trap.

In the present study, the heat transfer performance is examined. It is judged by a total thermal efficiency of the system $\overline{\eta}_{tot}$, which is defined as a summation of the thermal efficiency in each heat transfer component as shown by equation (1),

$$\overline{\eta}_{tot} = \overline{\eta}_{tb} + \overline{\eta}_{ft,right} + \overline{\eta}_{ft,left} \quad (1)$$

where $\overline{\eta}_{tb}$ $\overline{\eta}_{ft,right}$ and $\overline{\eta}_{ft,left}$, respectively, are defined as ratio of the rate of heat absorbed by the water flowing in the tube bank, the right-hand side flame trap and the left-hand side flame trap to the firing rate (CL). Thermal efficiency for each component is computed based on a time-average exit temperature of water, which is varied with time when operating with the CFRC mode.

Emission analysis of the dry combustion products at the reactor exit is carried out by using the Messtechnik Eheim model Visit01L, which is a portable emission analyzer designed especially for quasi-continuous measurement. A gas processing system of NO_x and CO is especially tuned for electrochemical sensors, ensuring long-time stability and accuracy of measurement. The measuring range of the analyzer is 0-4,000 ppm for NO_x and 0-10,000 ppm for CO with measuring accuracy of about $\pm$5 ppm (from the measured value) and resolution of 1 ppm for both NO_x and CO. All measured emissions in the experiment are those corrected to 0% excess oxygen and dry-basis. Repeated measurement shows an uncertainty of about 10% for the species concentrations.

2.3 Procedure

Combustion was started by operating the OWFC mode with the flow direction fixed at the forward flow (see Fig. 1) before switching to the CFRC mode. Preheating of the packed bed is required, and is achieved by combustion of a small auxiliary gas burner put into the opening window on top of the test unit. During this preheating period, only the flame traps are supplied by water with the total amount of mw_{ft} = 5.7 kg/min, whereas the tube bank is not. Then premixed gases with an initial equivalence ratio Φ close to one (ratio of the stoichiometric air required to the actual air supplied) are supplied into the test unit at a typical firing rate CL of about 10 kW. Once ignition is accomplished, the auxiliary gas burner is removed, and the heat input and the equivalence ratio are adjusted to obtain the desired level. During this course flame stabilized at upstream side of the tube bank of row 1 and then the water is supplied to the row 1 to prevent it from over heating. With the same reason, water is supplied to the other tube of row 2 and row 3 as firing rate is gradually increased until steady condition of the OWFC mode is reached. As a strong quenching effect is involved, a relatively high temperature of more than 600°C of the packed bed at downstream side of the tube bank is required for possible auto-ignition when the flow direction in reversed. Then the system is switched to the CFRC with a typical switching period t_{hp} = 30 s. During this course, the firing rate CL, the switching period t_{hp} and total mass flow rate mw_{tb} are adjusted to maintain high temperature level within the reactor and optimal exit temperature of the tube bank and the flame traps until the quasi-steady state is established. All numerical values of the important operating conditions appearing in the experiment are summarized in Table 1.

Table 1. Operating conditions.

Quantity	Value
Average diameter of alumina pellets, d_p	16 mm
Equivalence ratio, Φ	0.65
Firing rate, CL	14.6 kW
Inlet temperature of water, $Tw_{ft,i}$, $Tw_{tb,i}$	303 K
Inlet gas temperature, T_i	303 K
Longitudinal pitch, S_L	30 mm
Low heating value of LPG	115 MJ/m^3 [normal]
Number of tubes of tube bank	8
Switching period, t_{hp}	30–390 s
Total water flow rate at tube bank, mw_{tb}	7.2 kg/min
Total water flow rate at flame traps, mw_{ft}	5.7 kg/min
Transverse pitch, S_T	30 mm
Tube inside diameter, D_i	9 mm
Tube outside diameter, D_o	13.5 mm

3. Results and discussion

Possibly the most important variable from a performance optimization standpoint is the effect of switching period t_{hp}. Changing the switching period alone may strongly affect the combustion stability (movement of the hot zone) in the porous matrix, which in turn strongly affects the thermal performance, combustion characteristics and emissions. A too long switching period can result in overcooling of the hot zone because the hot zone was pushed closer to the tube bank, whereas a too short switching period can cause incomplete combustion because of too limited combustion time. Therefore, an optimal switching period could be found at a fixed superficial gas velocity. All tests were conducted at a fixed firing rate CL = 14.6 kW and equivalence ratio Φ = 0.65, but with variable switching period from 30 to 390s.

The effect of switching period t_{hp} on a cycle-averaged, solid phase temperature $\overline{\overline{T}}$ is shown in Fig. 3. Here, $\overline{\overline{T}}$ was employed because of an asymmetrical shape of the half-cycle averaged temperature for FW and BW. The measured $\overline{\overline{T}}$ within the reactor can be used to indicate a tendency to movement of the hot zone.

Since the heat input to the reactor is proportional to the switching period t_{hp}, changing in the switching period has a dramatic change in the reactor temperature. At the smallest switching period of t_{hp} = 30s, relatively low temperature $\overline{\mathbf{T}}$ prevails over the tube bank. The highest thermal efficiency occurs at the flame traps ($\overline{\eta}_{ft,right}$ and $\overline{\eta}_{ft,left}$) with summation in their thermal efficiencies exceeding 40%, and the lowest thermal efficiency of about 35% at the tube bank $\overline{\eta}_{tb}$ as shown in Fig. 4.

At t_{hp} = 30 s, the hot zone stabilizes near the flame traps rather than the tube bank with moderately high $\overline{\mathbf{CO}}$ emission of about 500 ppm but with very small concentration of $\overline{\mathbf{NO}}_{\mathbf{X}}$ as shown in Fig. 5. It is important to note here again that $\overline{\mathbf{NO}}_{\mathbf{X}}$ is very low of about 30 ppm throughout the range of study and is insensitive to the change in the switching period and $\overline{\mathbf{T}}$.

However, as the switching period increases, the temperature $\overline{\mathbf{T}}$ in the middle region of the tube bank steadily increases, whereas those near the reactor terminals slightly decreases. As a consequence, $\overline{\eta}_{tb}$ steadily increases accompanied by the total thermal efficiency $\overline{\eta}_{tot}$, whereas thermal efficiency at the flame traps, particularly at the right-hand side flame trap $\overline{\eta}_{ft,right}$ clearly shows a decreasing trend as shown in Fig. 4. This indicates travel of the hot zone far a way from the flame traps with an increase in the switching period, resulting in a more complete combustion with $\overline{\mathbf{CO}}$ reduction until the minimum value of about 200 ppm was reached at t_{hp} = 120s as shown in Fig. 5. The total thermal efficiency $\overline{\eta}_{tot}$ as high as 85% was achieved at t_{hp} = 180s. Therefore, optimal switching period of about t_{hp} = 120-180s was found at which the $\overline{\mathbf{CO}}$ emission become minimum, whilst $\overline{\eta}_{tot}$ become maximum.

Further increase in the switching period of more than 180s leads to further increase in the reactor temperature $\overline{\mathbf{T}}$, particularly at the tube bank (Fig. 3) with almost constant $\overline{\eta}_{tb}$ but lower $\overline{\eta}_{ft,right}$ and $\overline{\eta}_{ft,left}$ (Fig. 4). However, this is accompanied by an incomplete combustion with a significant increase in $\overline{\mathbf{CO}}$ (Fig. 5). This may be attributed to a substantial movement of the hot zone towards the tube bank, which can be observed by a shift in the location of the maximum $\overline{\mathbf{T}}$ closer to the tube bank, particularly on the right-hand side of the tube bank at relatively long switching period ($t_{hp} \geq$ 300 s) (Fig. 3). However, movement of the hot zone on the left-hand side of the tube bank was not as clear as the right-hand side one because of complex phenomenon of fluid dynamics, heat transfer, combustion and their interaction within the porous matrix.

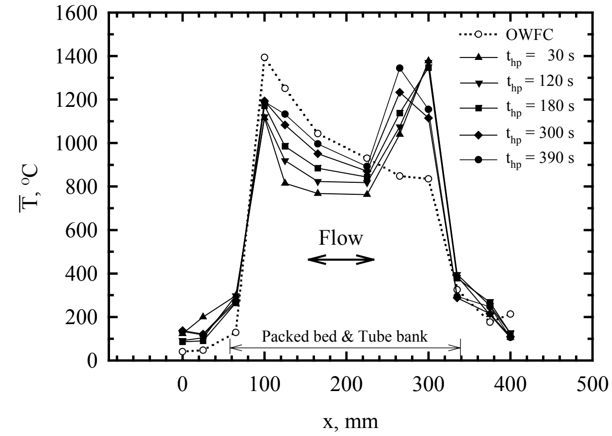

Fig. 3. Effect of t_{hp} on $\overline{\mathbf{T}}$.

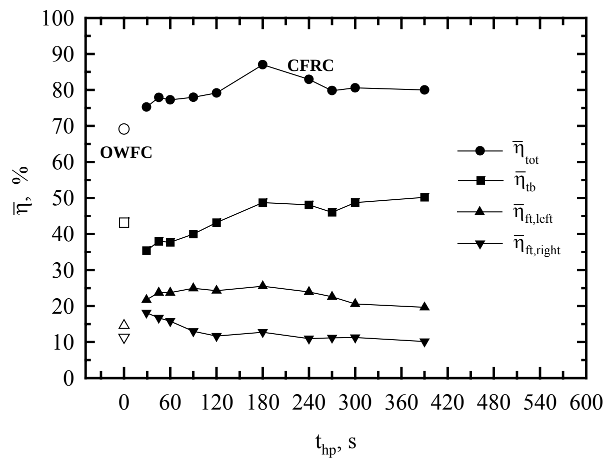

Fig. 4. Effect of t_{hp} on $\overline{\eta}$.

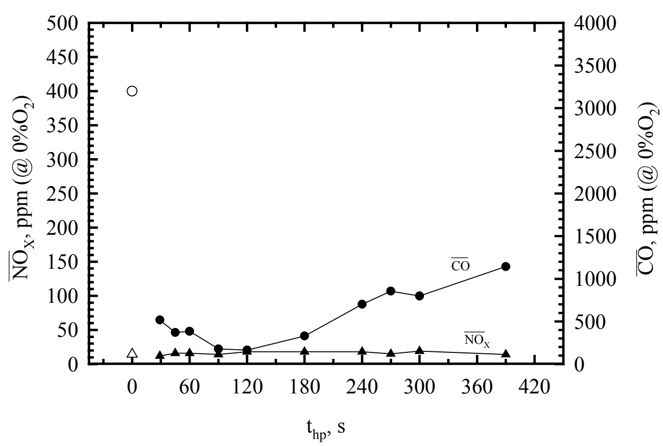

Fig. 5. Effect of t_{hp} on $\overline{\mathbf{CO}}$ and $\overline{\mathbf{NO}}_{\mathbf{X}}$.

Ultimately, longer t_{hp} beyond 390s leads to the system equivalent to the OWFC with the hot zone stabilized within the reactor at either upstream or downstream side of the tube bank depending on the flow direction being specified. For the OWFC system with the forward flow direction as shown in Fig. 3, it seems that the hot zone for the OWFC was strongly pushed towards the tube bank such that overcooling was occurred, resulting in relatively high CO emission of about 3,200 ppm (Fig. 5) with relatively low total thermal efficiency $\overline{\eta}_{tot}$ (Fig. 4) of about 70%. Substantial reduction in CO emission simultaneously with improvement in $\overline{\eta}_{tot}$ can be achieved by switching to the CFRC mode. Then, all the packed bed of the porous matrix will be involved not only in the combustion but also the heat transfer to the tube bank. Therefore, improvement in thermal efficiency and emission (CO) can be achieved by the CFRC system with less severe hot spots because of a more uniform temperature profile along the bed.

Neither OWFC nor CFRC mode can yield the hot zone moving into the tube bank. This may be attributed to a strong quenching effect caused by the considered tube bank configuration with the tube coils quite closely spaced. An ideal condition of overlapping of the hot zone with the tube bank can not be achieved unless the strong quenching effect is relaxed. This supports the conclusion that tube bank configuration plays an important role in the interaction between the tube bank and the hot zone, which in turn strongly affect the thermal performance, combustion characteristics and emissions. Changing in configuration of the tube bank that can allow for entering of the hot zone into the tube bank of the CFRC system is the subject of an on-going investigation.

4. Conclusion

4.1 The CFRC system demonstrates very dynamic behavior, with a complex inter-relationship with the switching period. The switching period strongly affect thermal performance and emissions through the interaction of movement of the hot zone and the heat transfer to the embedded tube bank. The optimal switching period of about 120-180 s was found within the range studied with maximum thermal efficiency as high as 85% with low emission of CO and NO_X of 200 ppm and 30 ppm, respectively. However, the goal of the study of determining a reliable method for obtaining an overlapping of the hot zone with the tube bank using variation in the switching period was not realized until the strong quenching effect caused by the closely spaced tube bank is relaxed.

4.2 At the same experimental condition, CFRC can yield higher thermal efficiency than the OWFC system with a significantly lower CO emission. However, both systems yield almost the same value of $\overline{NO}_X$, which could be considered as independent of the system.

References

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