A New Concept of Boiler Using a Cyclic Flow Reversal Combustion Technology (CFRC) of Mixture in a Porous Medium

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Abstract

Successive research on a new surface combustor-heater (SCH) equipped cyclic flow reversal combustion (CFRC) technique was explored. Possible maximum thermal efficiency with favorable emission characteristics was pursued through furnace modifications and past experience. It is suggested that a well-controlled boundary condition at the ends of the packed bed combustor could improve furnace thermal efficiency. Type of the packed bed also plays a vital role in improving furnace efficiency. Based on the existing experimental apparatus, modification was made in accordance with the two major aspects. Combustor performance were examined and evaluated. Some important operating parameters were clarified. Merits of this kind of combustor were also suggested. Result shows that the additional flame traps play an important role in maintaining the boundary condition of the packed bed. An increase in the thermal efficiency from 40 % to 66 % with a drastic reduction in CO from 700 ppm to 170 ppm and NO_X from 32 ppm to 14 ppm was achieved as compared with the previous data. Desirable trapezoid-like shape temperature profiles were achieved by increasing size of the alumina sphere (d_p) form 6 mm to 16 mm. Mass flow rate of the cooling water of the tube bank strongly affect thermal efficiency and emission characteristic. Thermal input appreciably affects thermal efficiency but moderately affects the CO and NO_X emissions. The CFRC can yield almost twice higher heat transfer performance than that of the OWFC with a much smaller CO and NO_X emission. The CFRC concept can provide the basis for development of state-of-the-art technology for a new version and a more advanced thermal systems such as, highly efficient ultra-low pollutant emission boilers, water heater, steam super heaters and thermal fluid heaters for efficient utilization of energy.

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1. Introduction

With the advent of the CFRC [1] and the SCH [2], the new SCH equipped with the concept of the CFRC was first proposed by Jugjai et al. [3, 4]. Considerable practical benefits of the new SCH as compared with the conventional OWFC were revealed [3, 4]. These are a more favorable flame stabilization with extended flammability, a more uniform temperature profile in the combustion chamber with higher heat transfer performance and a much smaller emission of CO and NO_X. Nevertheless, further improvement in the thermal efficiency of the new SCH can be obtained by changing the boundary conditions of the packed bed and by changing type of the packed bed as suggested by Jugjai et al. [4]. This becomes the main topic in the present study.

The main objective of this study is to further develop the new version of the SCH equipped with the CFRC with some modifications at the packed bed and its boundary condition. Transient behavior under the modification of the system is observed. Improvements in thermal efficiency and emission characteristics are judged by comparing results with the previous data [4]. Effects of various parameters such as, mass flow rate of the cooling water at the tube bank (mw_{tb}) and the heat input (CL) are clarified. Again, performance of the CFRC will be assessed by making a comparison with those of the conventional OWFC through temperature profile, thermal efficiency and emission characteristics.

2. Experimental apparatus and procedure

Fig. 1 shows an experimental apparatus of the recently developed new version of the SCH. The design concept, operational function, experimental apparatus and instrumentation are quite similar to those of the previous one [4]. However, some

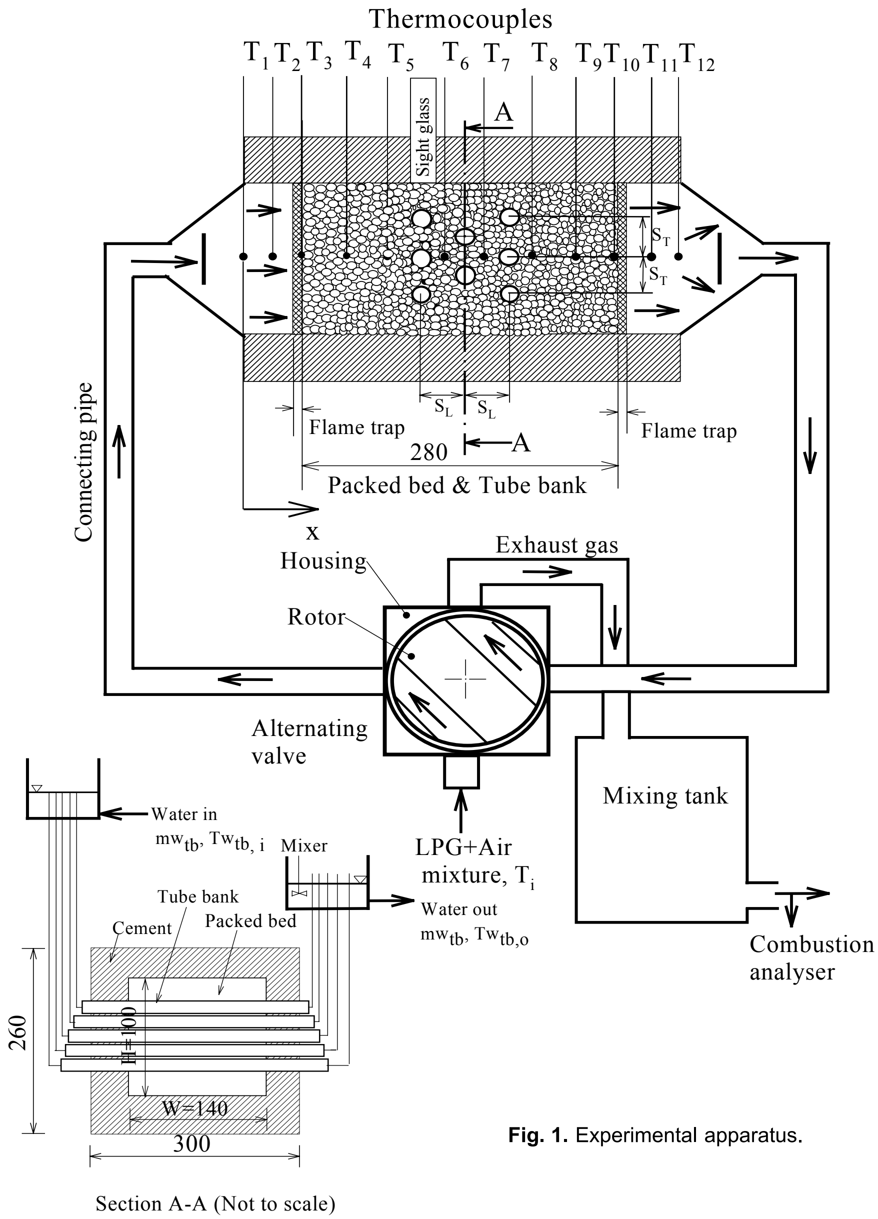

Fig. 1. Experimental apparatus.

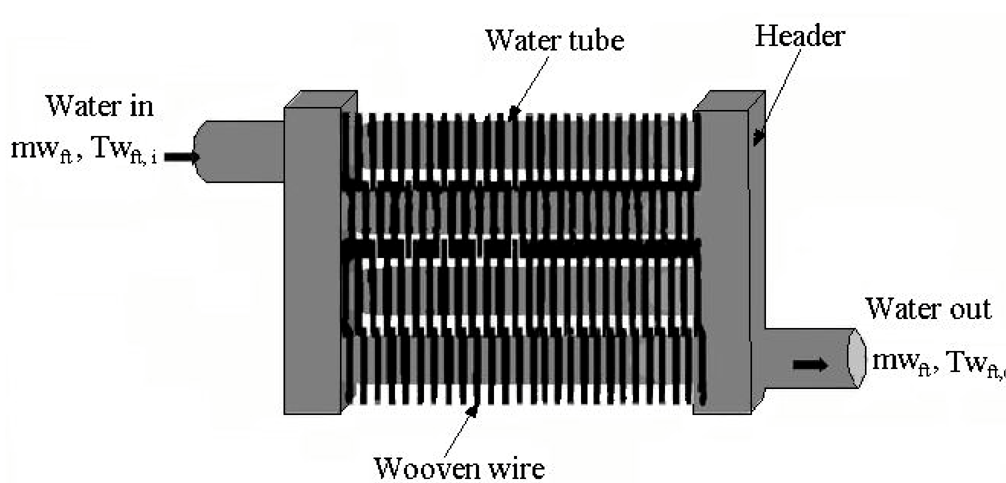

Fig. 2. Flame trap.

modifications were made in three points, Firstly, the present apparatus totally consists of a randomly packed bed of solid alumina spheres, not partially consists of the spheres at the tube bank with a stack of pieces of rectangular honeycomb porous ceramic plates flanged on both sides as the previous apparatus [4]. Secondly, the diameter d_p of the alumina sphere is increased from 5 mm to 16 mm so as to increase the pore size and to reduce flame quenching during it's propagation inside the packed bed. Thirdly, two flame traps as shown in Fig. 2 with each one is installed at each end of the packed bed to minimize radiative heat loss and to prevent the flame from being pushed out of the pack bed. The flame traps also serve as the heat exchanger in which the useful heat can be extracted from the supplied cooling water.

To allow very high temperature measurement, B-type sheath thermocouples T_1 to T_{12} of wire diameter 0.5 mm were used instead of N-type as the previous study [4]. Other quantity, such as inlet and outlet bulk temperatures of the cooling water in the tube bank and in the flame traps, water mass flow rate, fuel mass flow rate, combustion air mass flow rate as well as gas temperatures and emission of CO and NO_X are still measured by the same equipment as the previous study [4]. A quasi-steady state condition of the CFRC was reached once the constant amplitude and the constant average over a haft-period (t_{hp}) of the fluctuation temperatures T_1 to T_{12} were obtained. The operating procedures of the burner for both the CFRC and the OWFC are quite similar to those of the previous study [4] and the detailed explanation is omitted here.

In the present study the heat transfer performance and the combustion characteristics are examined. The heat transfer performance is judged by total thermal efficiency of the system (η_{tot}), which is defined as summation of the thermal efficiency at the tube bank and at the frame traps as shown in equation (1),

$$\eta_{tot} = \eta_{tb} + \eta_{ft} \qquad (1)$$

where η is defined as ratio of the rate of heat transferred to the water in the tube bank or to the flame traps to the total heat supplied (CL) of the system. The combustion characteristics are evaluated from the measured NO_X and CO concentrations. The numerical value of the important quantities appearing in the experiment are summarized in Table 1.

Table 1. Operating conditions

Quantity	**Value**	
Average diameter of alumina sphere, d_p	6, 16	mm
Bed height, H	100	mm
Bed width, W	140	mm
Bed length, L	280	mm
Cooling water mass flow rate at tube bank, mw_{tb}	2.7—7.6	kg/min
Cooling water mass flow rate at flame trap, mw_{ft}	2 x 0.88—2x 1.56	kg/min
Equivalence ratio, Φ		
	0.38—0.49	for the CFRC
	0.49—0.79	for the OWFC
Half-period, t_{hp} (CFRC only)	10—45	s
Inlet cooling water temperature, $Tw_{ft,\,i}$, $Tw_{tb,\,i}$	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	
Thermal input, CL	8.08—18.10	kW
Transverse pitch spacing, S_T	30	mm
Tube inside diameter, D_i	9	mm
Tube outside diameter, D_o	13.5	mm

3. Results

3.1 Effect of flame the trap on boundary condition, thermal efficiency and emission characteristics.

Effect of the flame trap on the boundary condition at both ends of the packed bed can be studied by comparing transient temperature profiles as shown in Figs. 3 and 4 at almost the same experimental conditions. With flame trap (Fig. 4) amplitude of the temperature swing at both ends of the packed bed were significantly reduced. Upon changing the flow direction from the backward flow to the forward flow in the two systems without and with the flame trap, the inlet temperature change with time t from t = 0 to t = t_{hp} shows an opposite trend. Without the flame trap (Fig 3), the hot zone deep inside the packed bed from the inlet is strongly quenched by the in flowing cool mixture resulting in decreasing in the temperatures. On the other hand, a more stable hot zone at relatively high temperature level with increasing in the inlet temperature with time t was achieved in the flame trap system (Fig. 4). Even though the concave temperature profiles were achieved in the flame trap system, higher thermal efficiency η_{tot} with significantly lower CO and NO_X emission than those of the system without flame trap were achieved as shown in Fig. 5. The flame trap system yields maximum η_{tot} = 66 % with small amount of CO = 170 ppm and NO_X = 14 ppm, whereas the system without flame trap yields maximum η_{tot} = 40 % with

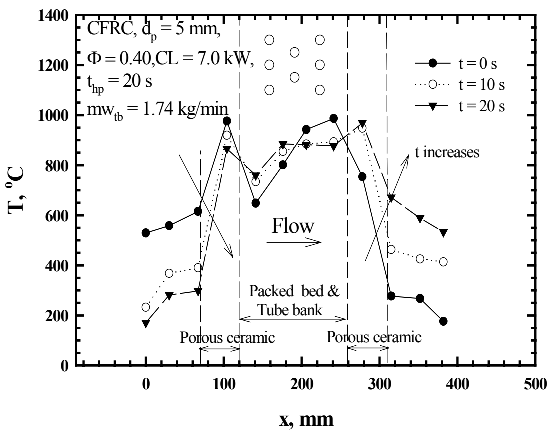

Fig. 3. Typical transient temperature profiles of the CFRC. (without flame trap)

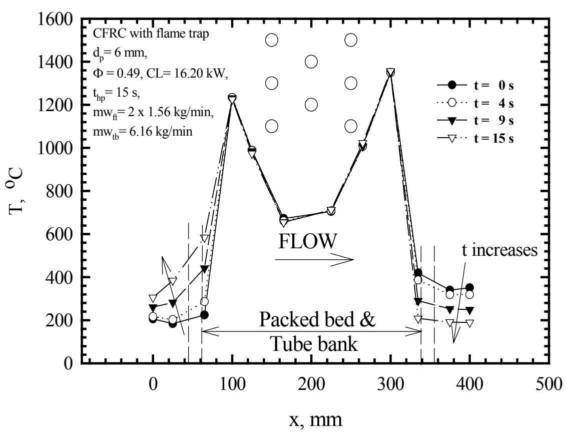

Fig. 4. Typical transient temperatures profiles of the CFRC. (with flame trap)

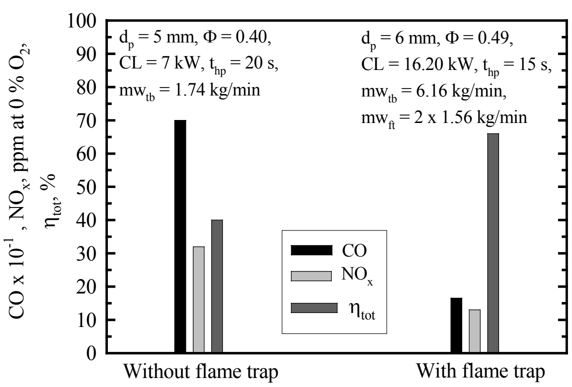

Fig. 5. Comparison of CO, NO_X and η_{tot} between with- and without flame trap for the CFRC.

relatively high CO and NO_X emission of about 700 ppm and 32 ppm, respectively. Thus, the flame trap system yielded 26 % higher thermal efficiency with a more complete combustion with extremely low NO_X emission as compared with the system without flame trap.

3.2 *Effect of mass flow rate of the cooling water at the tube bank, mw_{tb}*

Because of the transient nature, temperatures of the CFRC were averaged over a half-period (t_{hp}) before making any explanations, Desirable trapezoid-like shape time-averaged temperature (T_{av}) profiles in an interval t_{hp} were achieved during a preliminary study of effect of the size of the alumina sphere (d_p). This occurred when d_p was increased from 6 mm to 16 mm. Then, mw_{tb} was varied so as to understand change in the temperature profiles and to obtain possible maximum η_{tot}. Results are shown in Figs. 6 and 7. η_{tot} was largely dependent on mw_{tb} as shown in Fig. 7. However, at a certain value of mw_{tb}, i. e. mw_{tb} = 6.43 kg/min, unsymmetrical temperature profile was yielded and the maximum temperature zone was shifted far away from the tube bank as shown in Fig.6, causing a drastic decrease in η_{tot}. Flame quenching by the tube bank was also significantly reduced with the unsymmetrical flame shape resulting in a drastic decrease in CO emission as shown Fig 8, η_{ft} has a small contribution to η_{tot} so long as the temperature profile become symmetry. In spite of the occurrence of the unsymmetrical flame, η_{ft} could be significantly increased by increasing the water flow rate mw_{ft} of the flame trap locating on the same side as the hot zone is shifted. This provides an optional means for maintaining high total thermal efficiency. It is interesting to not that the NO_X emission of less than 40 ppm was observed throughout the experimental range.

3.3 *Effect of thermal input CL*

To studied turndown ratio of the system, CL was increased from 8.08 kW up to 18.10 kW as shown in Figs. 9 to 11. CL of more than 18.10 kW was not performed due to excessively high temperature. As CL increases, T_{av} remarkably increases throughout the bed length except at the flame trap locations as shown in Fig. 9. However, η_{tot} shows a decreasing trend as CL increases as shown in Fig. 10 because of the high heat loss through the combustor wall and through the exhaust gases with high velocity. In spite of a significant increase in T_{av} with CL, almost insignificant change of CO and NO_X emission were observed as shown in Fig. 11. Note that CO and NO_X emission of

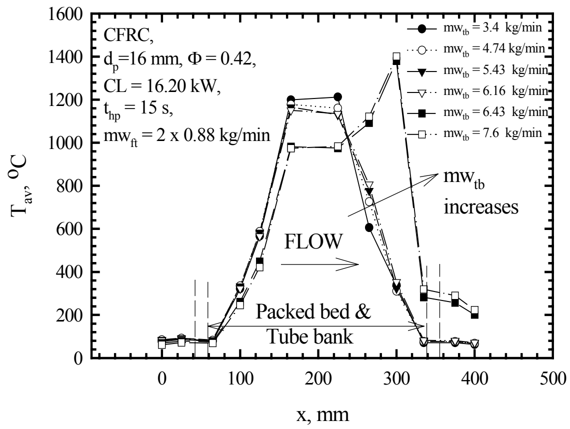

Fig. 6. Effect of mw_{tb} on time averaged temperature profiles T_{av}.

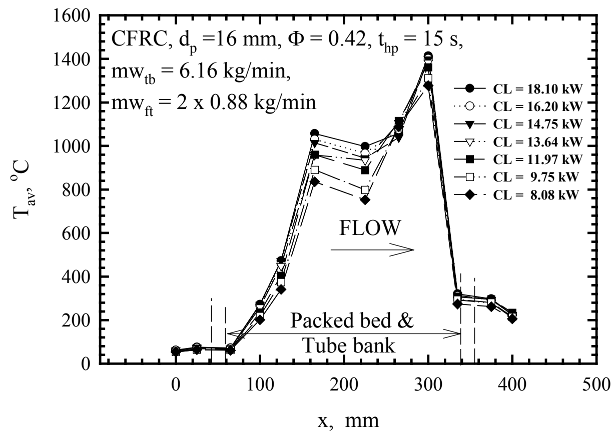

Fig. 9. Effect of CL on time averaged temperature profiles T_{av}.

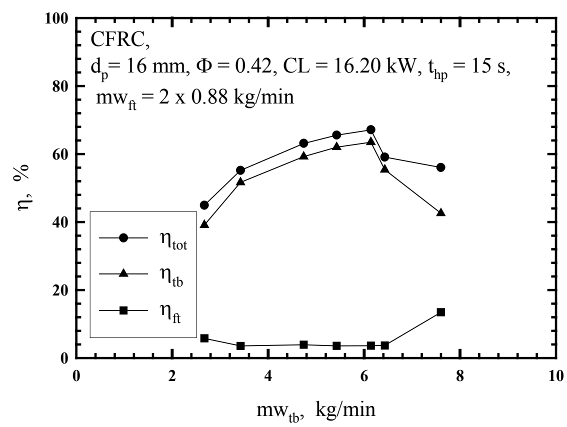

Fig. 7. Effect of mw_{tb} on η.

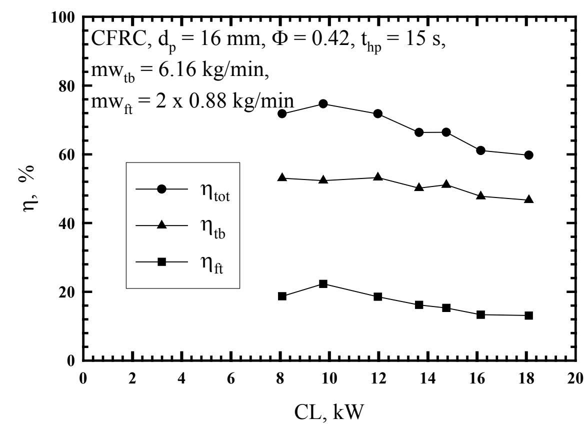

Fig. 10. Effect of CL on η.

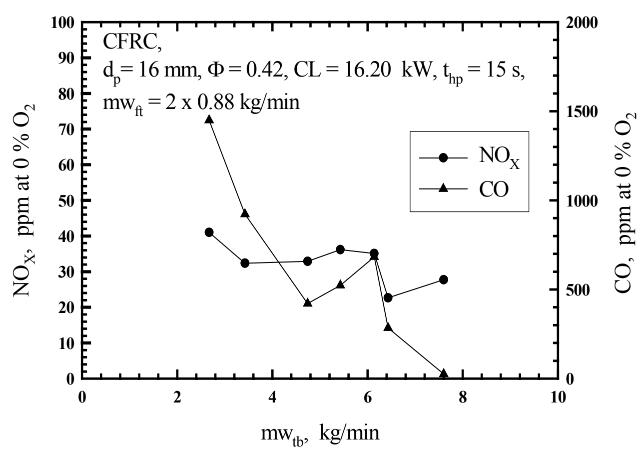

Fig. 8. Effect of mw_{tb} on NO_x and CO.

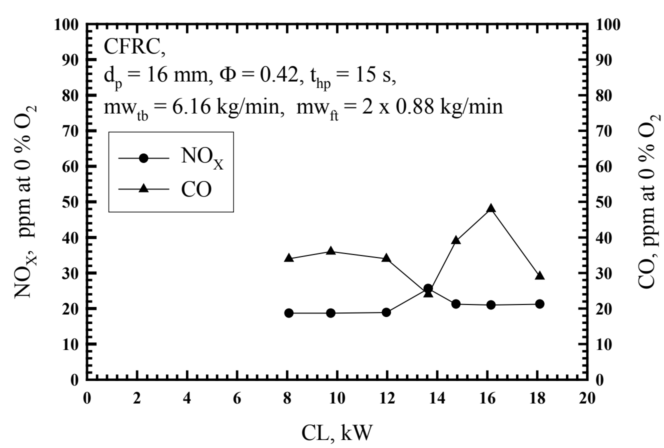

Fig. 11. Effect of CL on CO and NO_X.

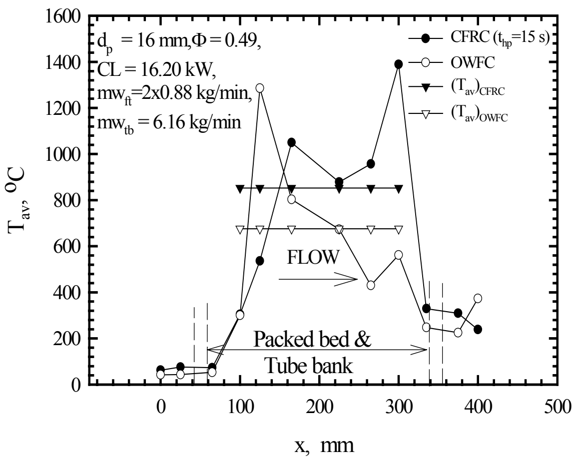

Fig. 12. Comparison of typical T_{av} between CFRC and OWFC.

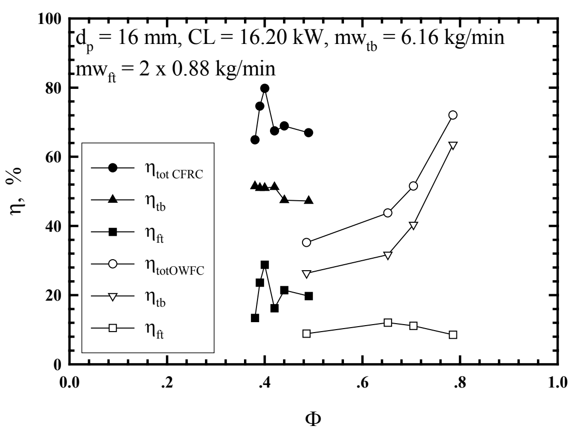

Fig. 13. Comparison of η_{th} between CFRC and OWFC

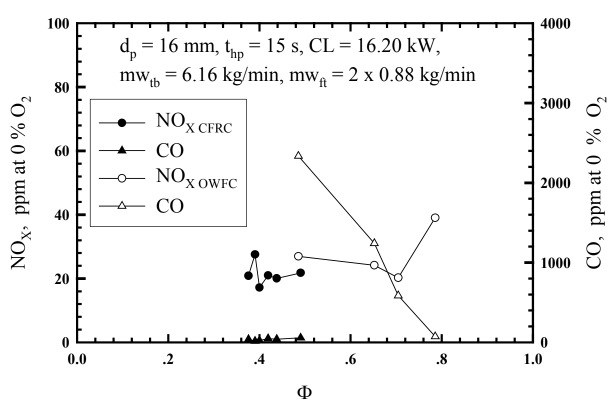

Fig. 14. Comparison of CO and NO_x between CFRC and OWFC.

less than 30 ppm and 50 ppm, respectively, were yielded throughout the experimental range.

3.4 *Comparison between the CFRC and the OWFC*

Fig. 12 shows a comparison of the temperature profiles between the OWFC and the CFRC at the same experimental conditions. The CFRC yielded higher maximum temperature and higher averaged temperature over the tube bank $(T_{av})_{CFRC}$. At the same Φ = 0.49, the CFRC yielded almost twice as high as η_{tot}, η_{tb} and η_{ft} with less CO and NO_X emission than the OWFC as shown in Figs. 13 and 14. Almost zero CO emission and NO_X of less than 30 ppm were observed for the CFRC. The CFRC is suitable for relatively lean combustion, whereas the OWFC is suitable for relatively rich combustion with comparable total thermal efficiencies and emission characteristics.

4. Conclusions

Flame trap plays an important role in maintaining the boundary condition of the packed bed, whilst improving thermal efficiency and combustion characteristics. Optimum mass flow rate of the cooling water of the tube bank was 6.16 kg/min, which yields maximum thermal efficiency. Increasing the thermal input appreciably increases the temperatures but decreases the total thermal efficiency without significant change in CO and NO_X emissions. At the same experimental condition, the CFRC can yield almost twice higher thermal efficiency than that of the OWFC with a much smaller CO and NO_X emission. The CFRC is suitable for lean combustion, whereas the OWFC is suitable for rich combustion with comparable total thermal efficiencies and emission characteristics. This system may be classified as a high efficiency, ultra-low emission, fuel-flexible boiler system.

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