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Effect of Scale-up on Heat Transfer Characteristics of Cyclone Separators of Circulating Fluidized Beds

R.S. Patil*, P. Mahanta*+[1] and M. Pandey+

Abstract – *Present study has been completed on heat transfer behavior in the cyclone separators of different cross sections of three different cold circulating fluidized beds (CFBs). Steady state experiments were carried out by providing heat in the riser of a CFB and consequently examining bed-to-wall heat transfer in the cyclone separator. To study the effect of scale-up (increase in barrel diameter of cyclones) on heat transfer characteristics, experiments were conducted under similar operating conditions on three CFB setups. Cyclone design ratios i.e ratios of various dimensions of cyclone with respect to cyclone barrel diameter were maintained same for all cyclone separators belonging to three different CFB setups. Experiments were conducted twice on each CFB setup for same value of five non-dimensional air velocities at two different weights of sand inventory per unit area of the distributor plate(i.e. P = 1750 N/m*^{2} *and 3050 N/m*^{2}*). Effect of parameters such as superficial velocity of air and sand inventory (P) on heat transfer characteristics was investigated for individual cyclone. Local heat transfer coefficient along the height of cylindrical portion of cyclone separators were evaluated and compared. Also, bed temperature across the barrel diameter of all cyclone separators were measured and compared. Empirical correlation was developed. Prediction of this correlation was in agreement (± 14.31%) with experimental data.*

Keywords – Bed temperature, CFB, cyclone separators, heat transfer coefficient, scale-up.

1. INTRODUCTION

Cyclone separator in the circulating fluidized bed (CFB) boiler handles a large volume of gas at high temperature. The unburned char particles entrained through the riser passes through the cyclone separator along with volatile and flue gases. Extent of combustion inside the cyclone is small due to less residence time and insufficient oxygen. However, additional combustion of carbon monoxide and the volatiles often occur in the cyclone. The outer skin temperature of the cyclone is relatively high incurring excessive heat losses due to natural convection and radiation. Recovery of the heat is accomplished in many cases by circulation of cool water or saturated steam to convert it into superheated steam. Thus there is scope to increase the capacity of the CFB boiler through extraction of heat from the cyclone separator [1].

Some results on the heat transfer characteristics in a cyclone separator of a CFB were reported by [2]. Nag and Gupta [3] had reported on the effect of fins on the average heat transfer coefficient inside the cyclone separator for different operating parameters like solid circulation rate, gas superficial velocity and pressure drop. Gupta and Nag [1] had discussed on wall-to-bed heat transfer behaviour in the cyclone separator of a cold CFB set-up of 10.2 m × 10.2 m riser cross-section, 5.25 m height. An empirical equation was developed to predict the heat transfer coefficient in the cyclone separator based on dimensional analysis. Patil *et al.* [4] had studied the effect of scale-up of cyclone on bed-to-wall heat transfer behavior of two different cold CFBs. They have reported that heat transfer coefficient increases with increase in cyclone barrel diameter and sand inventory.

Hydrodynamics of cyclone separator are reported by [5]-[10]. Dietz [5], Trefz and Muschelknautz [6] and Zhou and Soo [7] had reported on gas-solid flow structure and collection efficiency of the cyclone separator. They have reported that the cyclone efficiency decreases with increase in (a) cyclone diameter (b) gas outlet duct diameter (c) gas inlet area. Avci and Karagoz [8] had developed a mathematical model for the calculation of cyclone efficiency. Xiang and Lee [9] had discussed on the effects of exit tube diameter on the velocity profiles within cyclones. Theoretical analysis of pressure losses in the cyclone separators with different flow parameters including inlet geometry, surface roughness, velocity and particles concentration were discussed by Avci and Karagoz [10]. They have developed a correlation to predict the pressure losses. Therefore it is evident that most of the work has been completed on hydrodynamics and cyclone wall-to-bed heat transfer characteristics of single cyclone separator.

Therefore present work involves a comparative study of bed-to-cyclone wall heat transfer of cyclone separators of three different CFB units under similar operating conditions. Effect of other parameters such as sand inventory *(P),* superficial air velocity on the heat transfer along the axial and radial direction was studied for individual cyclone separator. Based on scale-up study, an empirical correlation for the Nusselt number with Reynolds number and two other non-dimensional numbers was developed.

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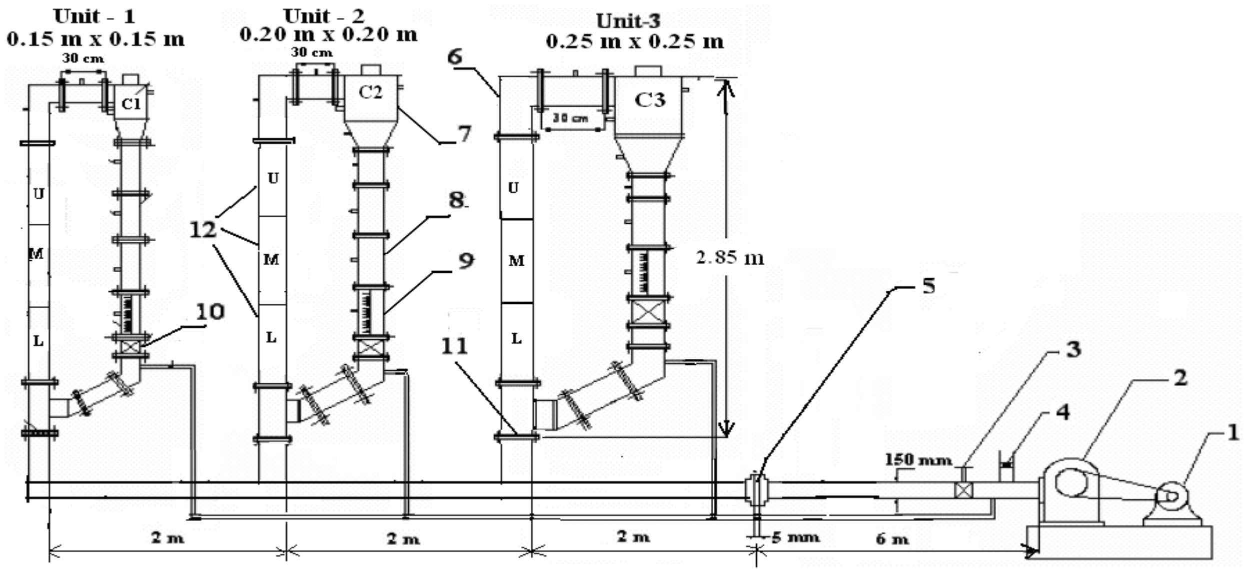
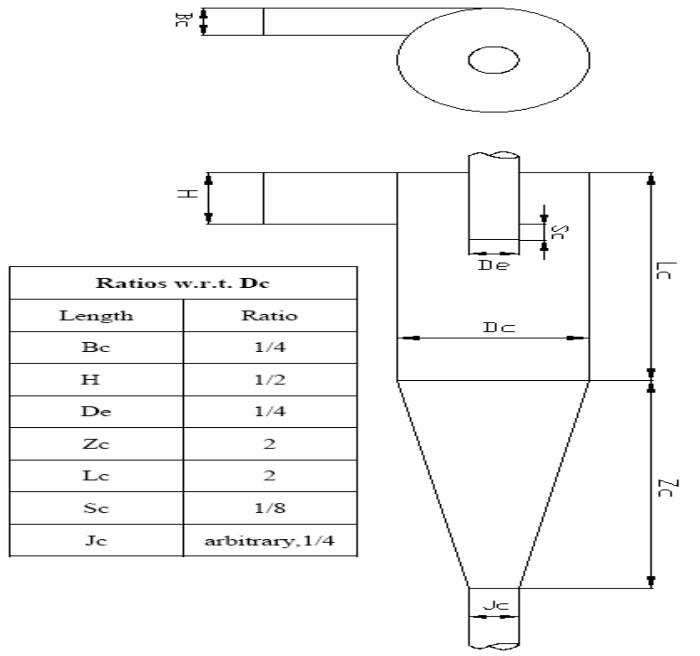
2. EXPERIMENTAL SETUP

The CFB setup was designed and developed at IIT Guwahati [11], as in Figure 1. A positive displacement type blower powered by a 20 HP motor supplies air. Parametric Studies were carried out on cyclone separators of three CFB setups with riser cross sections of 0.15 m × 0.15 m, 0.20 m × 0.20 m and 0.25 m × 0.25 m respectively. Cyclone separators (*C1, C2,* and *C3*) with barrel diameter (D_c) 0.27 m, 0.36 m and 0.45 m were used in the present study. Cyclone separators were fabricated with mild steel and design was made based on the procedure given by [12]. Various geometrical ratios of cyclone separator components were chosen based on [12] details of the same are enlisted in Figure 2. Local heat transfer coefficient in the cylindrical portion along the length (Lc) (refer Figure 2 and 3) of each cyclone was evaluated at the non-dimensional distance (Y/H_C) of 0.1, 0.2, 0.3, 0.4, 0.5 with respect to (T7-T11) respectively. Where the non-dimensional distance (Y/H_C) is the ratio of distance (Y) of the thermocouple location with respect to (T7-T11) as in Figure 3, measured from the inlet of the cyclone, normalized with respect to the total height of the cyclone ($H_C = L_C + Z_C$). Also, bed (sand and air mixture) temperature distribution in the radial direction of each cyclone was measured at five different locations at (T7-T11) as in Figure 3. Radial variations of temperature in barrel of the cyclones were measured at (T7-T11) in terms of non-dimensional distance (r/R), where (R) is the radius of the cyclone barrel and (r) is the location of the thermocouple from the centre of the barrel. Five *T*-type calibrated thermocouples (T2), (T3), (T4), (T5) and (T6) were used in the radial direction with non-dimensional distance (r/R) -0.9, -0.5, 0.0, 0.5, 0.9 respectively. While conducting the experiments, pressure taps were provided on the wall of the cyclone separator at locations T7 and T11 as shown in Figure 3. Using these pressure taps, pressure drop was obtained. Observed pressure drop in terms of (Δh) cm of water is used to calculate the voidage across the cyclone barrel diameter. Subsequently estimated voidage was used to calculate suspension density (solid holdup) of sand particles in the cylindrical portion of cyclone separator.



1. Motor
2. Blower
3. Bypass Valve
4. Safety Valve
5. Orifice Plate
6. Riser Column
7. Cyclone Separator
8. Downcomer
9. Sand Measuring Section
10. Butterfly Valve
11. Distributor Plate
12. Heater Section

Fig.1. CFB set-up.



Ratios w.r.t. Dc	
Length	Ratio
Bc	1/4
H	1/2
De	1/4
Zc	2
Lc	2
Sc	1/8
Jc	arbitrary,1/4

Fig. 2. Cyclone (C1, C2, C3) [12-13].

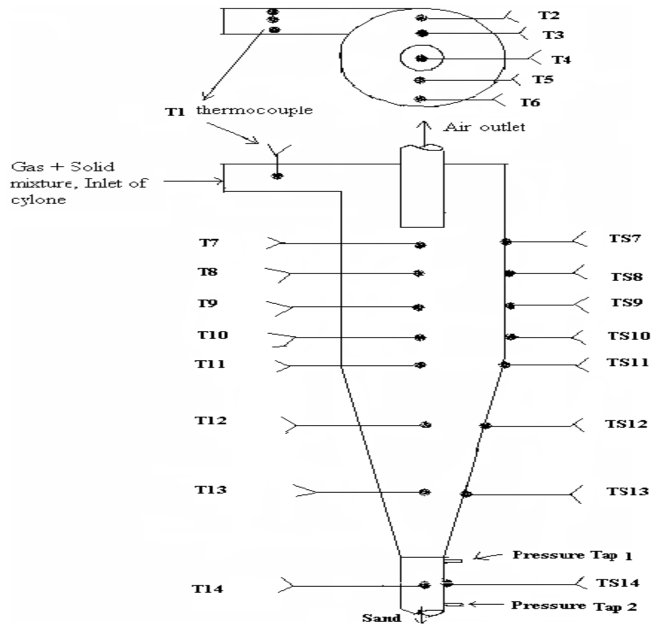


Fig. 3. Arrangement of thermocouples (C1, C2, C3).

3. HEAT TRANSFER STUDY

In the present study, heat was provided at the riser column with the help of a heater of length 0.6 m which is located at a height of 0.6 m above the distributor plate. Based on the cross-section of the riser, the dimensions of the heater of each CFB unit were different. Electric supply was provided to Nichrome wire wound on around the outer surface of the heater. A mica sheet of 1.5 mm thickness was used to prevent electric shock between the MS heater and the Nichrome wire. To avoid the heat losses by radiation, ceramic wool and 6 mm thick asbestos sheet was provided on the mica sheet. Heat is carried by sand and air mixture to the cyclone separator enabling the investigators to study the bed-to-cyclone wall heat transfer. Five thermocouples (T2), (T3), (T4), (T5) and (T6) were used to measure the bed temperature in the radial direction placed at (T7-T11) as in Figure 3. Thermocouples (TS7), (TS8), (TS9), (TS10) and (TS11) were used to measure the outer wall skin temperature of each cyclone separator as in Figure 3. Five thermocouples placed in the radial direction at locations (T7-T11) to measure the bulk mean temperature (T_B) of the bed. This facilitates the measurement of local heat transfer coefficient (h_C) along the height of the cyclone. Local heat transfer coefficient (h_C) along the height of the cyclone separator is calculated by

$$h_C = q'' / (T_B - T_S) \quad (\mathrm{W.m^{-2}.K^{-1}}) \qquad (1)$$

where (T_B) and (T_S) represents the bed and wall temperature respectively. Heat flux (q'') in each cyclone separator is calculated by

$$q'' = (q_1 - (q_2+q_3) / As \quad (\text{W/m}^2) \qquad (2)$$

where (q_1) is the amount heat carried by air + sand mixture which was calculated at the inlet of cyclone separator, (As) is the surface area of cyclone separator, (q_2) and (q_3) is the heat carried by gas and sand (in W) from the chimney and bottom outlet of cyclone separator, respectively. Speed and temperature of gas at outlet of cyclone was measured using anemometer. Experiments were accomplished on three cold CFB setups at same operating conditions. Experiments were conducted twice on each CFB setup for same value of five non-dimensional air velocities (U* = 5, 5.5, 6, 6.6 and 8) at two different weights of sand inventory per unit area of the distributor plate at riser (i.e. P = 1750 N/m^2 and 3050 N/m^2). Actual mass of sand on the distributor plate was 4 kg, 7 kg, 11 kg of small, medium and large size CFB unit to obtain the P = 1750 N/m^2 and it was 7 kg, 12.5 kg, 19.5 kg, respectively to obtain P = 3050 N/m^2. Average sand particle size was 460 µm for all the set of the experiments. Also, heat flux at the wall of the heater of each CFB setup was kept same as 1000 W/m^2 for all the set of experiments. As shown in Figure 1, the heater section was placed at portion L of the riser section. Air and sand mixture get heated in the heater section. Present work is the cold bed study and plexiglass columns were provided in the riser column above the heater section. To prevent the melting of plexiglass column and safety of Nichrome wire from its breakage at high voltage, heat flux provided at the wall of the heater was limited to 1000 W/m^2. Therefore, it is observed that bulk mean bed (air + sand mixture) temperature in the heater section was in the range of 33ºC-50ºC at different operating conditions. Hence range of temperature inside the cyclone separator was 30ºC-47ºC under which bed-to-wall heat transfer in the cyclone separator was conducted Local heat transfer coefficients in the axial direction along the height of the cyclone separator and bed temperature distribution in radial directions were obtained for each cyclone separator of different CFB setups under similar operating conditions. Trends obtained for all cyclones were compared with each other for the same operating conditions and effect of parameter like superficial air velocity and sand inventory *(P)* on heat transfer characteristics is predicted for individual cyclone in the next sections.

4. BED TEMPERATURE DISTRIBUTION

Figure 4 presents the effect of cyclone barrel diameter (D_C) on bed temperature distribution across a section located at non-dimensional distance 0.1 below the inlet of each cyclone of the different CFBs for the operating conditions, P = 3050 N/m^2, heat flux at the wall of the heater placed in the riser column of each CFB setup = 1000 W/m^2, non-dimensional velocity parameter (U^*) = 5, particle size (d_p) = 460 µm. Figure 4 shows average bed temperature across the section was less for larger size cyclone separator (*C3*) than smaller size cyclone separator (*C1*). This is because of average bed temperature across the heater section located in the CFB riser was less for larger size heater than smaller size heater. This is expected because sand inventory in larger cross section CFB setup was kept proportionately more than the smaller size CFB setup so as to maintain the same weight of sand per unit area of the distributor plate. Therefore, amount of sand particles suspended per unit surface area of the larger cross section heater was more than the smaller heater. Therefore at same heat flux applied at heater wall of each CFB setup, distribution of amount heat extracted due to conduction from wall of the heater took place into large number particles, which were comparatively more in lager cross section CFB setup, hence average bed temperature was less for lager size heater than smaller heater. Later same sand + air mixture with specific temperature enters the cyclone separator after its exit from riser outlet of each CFB setup. Therefore average bed temperature across the section was less for larger size cyclone separator (*C3*) than smaller size cyclone separator (*C1*).

Figure 4 may be compared with Figure 5 to examine the effect of velocity on bed temperature distribution across the section of specific cyclone. It was observed that increase in non-dimensional velocity parameter (U^*) from 5 to 8 resulted in decrease in bed temperature across the heater section of riser because holdup of sand particles transported near the wall of the heater decreases which subsequently decreases the heat transfer from wall-to-bed due to conduction. Same sand + air mixture with specific temperature enters the cyclone separator after its exit from riser outlet. Therefore bed temperature across the section found to be decreased with increase in non-dimensional velocity parameter (U^*) in each cyclone separator.

Figure 4 may be compared with Figure 6 to examine the effect of sand inventory *(P) on* bed temperature distribution across the section of specific cyclone. It is observed that bed temperature distribution across any heater section placed in the riser increases with increase in weight of sand inventory per unit distributor plate *(P*) from 1750 N/m^2 to 3050 N/m^2. This is because, the sand particles hold up increases near the wall of the heater which enhances the heat transfer due to conduction from wall-to-bed, which causes increase in heat contained by air + sand mixture hence its temperature for the air + sand mixture entering into the cyclone. Therefore bed temperature found to be increased in any cyclone with increase in sand inventory *(P).*

Figures 4-6 show the bed temperature was more at the core and less towards the wall of cyclone separator. This is because initially walls were at room temperature and temperature of hot stream of bed or mixture of air + sand was comparatively more. At the core, jet of air was formed which contains fine particles with temperature more than cyclone separator's wall temperature. After some time the temperature difference between wall and bed became less due to bed-to-cyclone wall heat transfer in the cyclone separator but trend of temperature distribution was same, more centre line temperature than wall temperature of cyclone as shown in Figures 4-6.

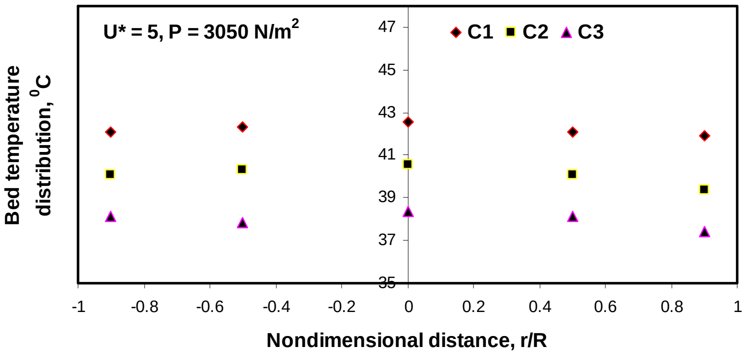


Fig. 4. Temperature distribution at U* = 5, P = 3050 N/m^2.

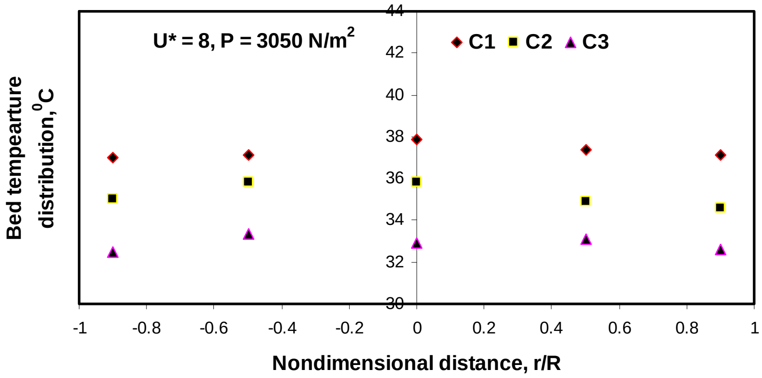


Fig. 5. Temperature distribution at U* =8, P = 3050 N/m^2.

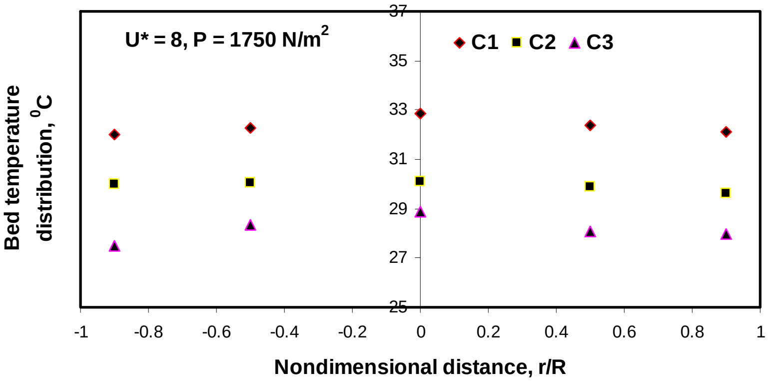


Fig. 6. Temperature distribution at U* = 8, P = 1750 N/m^2.

5. AXIAL DISTRIBUTON OF LOCAL HEAT TRANSFER COEFICIENT

Figures 7-10 show the axial distribution of local heat transfer coefficient along the height of each cyclone separator when three CFB setups were operated at same operating conditions. Figure 7 shows the axial distribution of local heat transfer coefficient along the cyclone height when three CFB setups were operated at same operating conditions at P = 3050 N/m^2, heat flux at the wall of the heater placed in the riser column = 1000 W/m^2, non-dimensional velocity parameter (U^*) = 5, particle size (d_p) = 460 µm. Local heat transfer coefficient for the larger cyclone separator (*C3*) was found to be more than other two smaller size cyclone separators (*C2* and *C3*). This is because of driving temperature difference (T_B – T_S) found to be lesser for the larger cyclone separator (*C3*) than cyclones separator (*C1*) and (*C2*). This is because amount of heated sand particles suspended per unit surface area of cylindrical portion of larger cyclone separator were comparatively more, resulted in lower thermal resistance from the bed-to-wall causing better heat conduction.

Heat transfer coefficient value was less at the top of the any cyclone at the non-dimensional distance of 0.1 because the temperature difference between sand + air mixture and wall of the cyclone separator was more compare to respective temperature difference at the non-dimensional distance of 0.5, as shown in Figures 7 to 10.

Figure 7 may be compared with Figure 8 to study the effect of velocity on the axial distribution of local heat transfer coefficient in any specific cyclone. Increase in fluidizing velocity reduces the wall-to-bed heat transfer in heater due to poor heat conduction caused due to decrease in sand particles hold-up near the wall of the heater and subsequently decrease in sand particles hold-up near the wall of the cyclone separator, which causes decrease in mixture (air + sand)-to-cyclone wall heat transfer due to poor conduction. Hence value of heat local heat transfer coefficient decreases with increase in non-dimensional velocity parameter (U*).

Figure 7 may be compared with Figure 9 to study the effect of sand inventory on the axial distribution of local heat transfer coefficient in any specific cyclone. Heat transfer coefficient increases with increase in sand inventory per unit area of distributor plate from to *P* = 1750 N/m^2 to 3050 N/m^2. This is because, solid hold-up near the wall of the heater and subsequently near the wall of the cyclone separator, which causes increase in mixture (air + sand)-to-cyclone wall heat transfer due to conduction in cyclone separator, hence value of heat local heat transfer coefficient increases with increased sand inventory *(P)*.

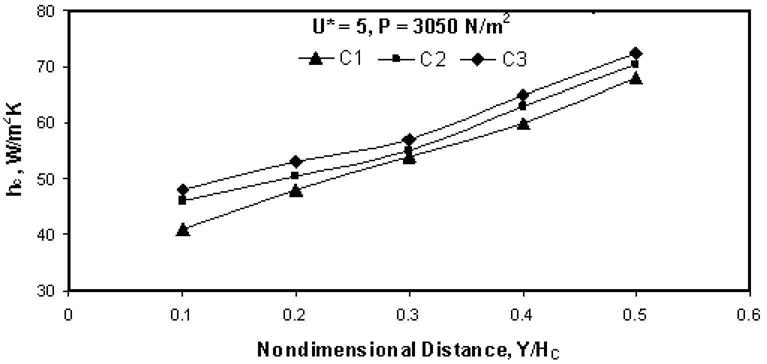


Fig. 7. Axial distribution of the local heat transfer coefficient at U* = 5, P = 3050 N/m^2.

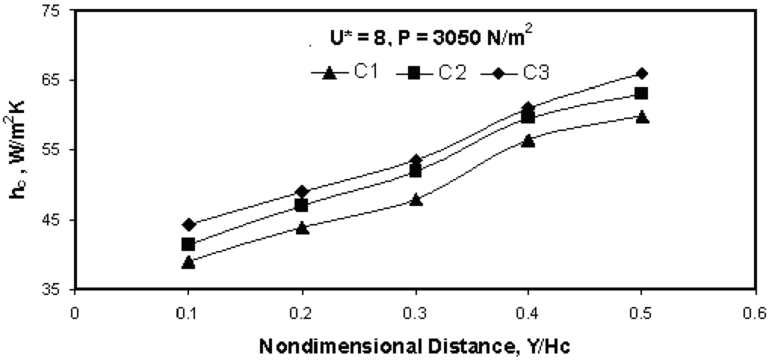


Fig. 8. Axial distribution of the local heat transfer coefficient at U* = 8, P = 3050 N/m^2.

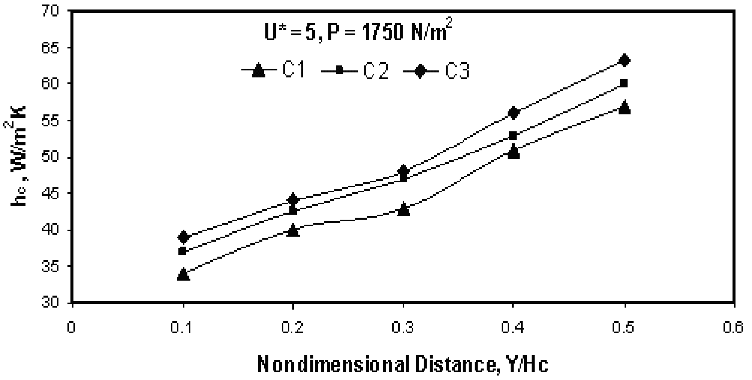


Fig. 9. Axial distribution of the local heat transfer coefficient at U* = 5, P = 1750 N/m^2.

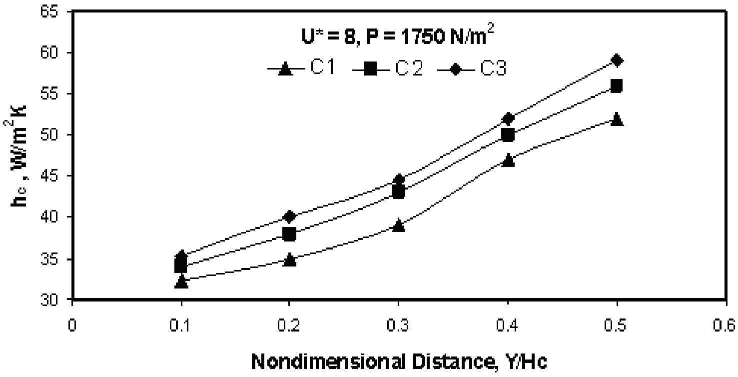


Fig. 10. Axial distribution of the local heat transfer coefficient at U* = 8, P = 1750 N/m².

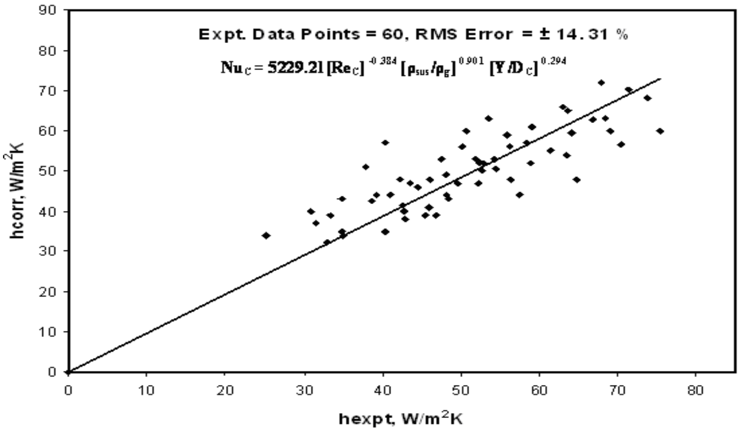


Fig. 11. Comparison of proposed correlation with experimental data (h_{corr}. Vs h_{expt}).

6. CORRELATION

A dimensional analysis was made using Rayleigh's method [14] and four non-dimensional numbers were obtained. Nusselt number and Reynolds number are the most important and widely used numbers. Also, two more Non-dimensional numbers were obtained, non-dimensional density ratio [ρ_{sus}/ρ_g] (ratio of suspension density of sand particles to the density of gas – air) and non-dimensional geometrical parameter (Y/D_C) (ratio of the distance (Y) of the different thermocouples location with respect to T7-T11 as in Figure 3, measured from the inlet of the cyclone, normalized with respect to barrel diameter of the cyclone (D_C)). A best-fit equation involving these four non-dimensional numbers fitting 60 experimental data points were obtained with the help of Findfit function of Mathematica [15]. The best-fit equation is as follows.

$$Nu_C = 5229.21[Re_C]^{-0.384}\,[\rho_{sus}/\rho_g]^{0.901}\,[Y/D_C]^{0.294} \qquad (3)$$

Above correlation is valid in the following range of experimental conditions: $15000 < Re_C < 42376$, $4 < \rho_{sus}/\rho_g < 18$, $0.2 < (Y/D_C) < 1$. The bed Nusselt number was in the range of 363.68 to 1350.

Figure 11 shows the comparison of the present experimental results with the prediction of the above correlation showing an rms deviation of ± 14.31%. Therefore less scatter (± 14.31%) indicate the accuracy of proper selection of different non-dimensional parameters used in developed correlation.

7. CONCLUSION

In the present study, effect of scale-up on heat transfer characteristics was studied in the cyclone separators of three different CFB setups operated at similar operating conditions. Scale-up study is important in the design point of view. Heat was supplied to the heater section placed in the riser column and consequently bed-to-wall heat transfer study was completed in the cyclone separators, which is realistic for present day CFB boilers. Comparative study has been completed to predict the effect of cyclone diameters on heat transfer characteristics and parametric study has been completed to predict the effect of superficial velocity of air and sand inventory on distribution of bed temperature in the radial direction in individual cyclone and heat transfer coefficient along the height of each cyclone. In all the cyclone separators, it was observed that the bed temperature decreases with increase in size i.e increase in cyclone barrel diameter, and superficial velocity of air. It increases with increases in sand inventory. Heat transfer coefficient increases with increase in barrel diameter of the cyclone separator and sand inventory. It decreases with increase in superficial velocity of air. Empirical correlation was developed to predict the Nusselt number. Less scatter (± 14.31%) from experimental data indicate the accuracy of proper selection of different non-dimensional parameters obtained for the developed correlation.

NOMENCLATURE

A_S	Surface area of the cyclone separator, (m)
$C1, C2, C3$	Small, medium and large sized cyclone separator
d_p	Sand particle size, (m)
D_c	Cyclone barrel diameter,(m)
h_C	Local heat transfer coefficient, (W/m^2.K)
H_C	Height of the cyclone ($L_C + Z_C$), (m)
L_C	Height of the cylindrical portion of the cyclone, (m)
Nu_C	Nusselt number, (hD_c/k_{air})
P	Static pressure due to weight of the sand inventory on the distributor plate in the riser column, (N/m^2)
q''	Heat flux for the cyclone separator, (W/m^2)
r/R	(r/R) is the ratio of distance (r) of the thermocouple location with respect to (T2-T6) measured from the centre of each cyclone to the radius (R) of that cyclone.
Re_C	Reynolds number, ($\rho_{air}V_{air}\, D_c/\mu_{air}$)
T_B	Bed (sand + air) mixture temperature, (K)
T_S	Wall temperature of cyclone separator, (K)
U^*	Non-dimensional velocity parameter, (ratio of fast fluidizing air velocity (U) to minimum fluidizing air velocity (U_{mf})).
Y/D_C	Non-dimensional distance (Y/H_C) is the ratio of distance (Y) of the thermocouple location with respect to (T7-T11) as in Figure 3, measured from the inlet of the cyclone, normalized with respect to the cyclone barrel diameter (D_C).
Z_C	Height of the conical portion of the cyclone, (m)
ρ_g	Density of gas – air, (kgm^{-3})
ρ_{sus}	Suspension density of sand,(kgm^{-3})

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