Parametric Studies and Effect of Scale-up on Heat Transfer Characteristics of Circulating Fluidized Beds

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Synopsis

Coal is the principal energy source in India because of its large deposits and availability. Coal has been extensively used in Indian power sector. Out of the total installed capacity of 147,965 MW, coal was in use to produce 93,725 MW (63.34%) during the year 2009. However, majority of coal in India contains high ash (as high as 45%) and sulphur (3-5%). With the existing technology, carbon dioxide, oxides of nitrogen and sulphur emitted by majority of the coal based power plants in India are significant attributing to environmental pollution. Therefore there is a great need for an alternative technology which can utilize this type of coal with its improved combustion and reducing pollution. A circulating fluidized bed (CFB) is a relatively new and alternate technology gaining popularity in power generation because of its capability of burning wide range of fuels including coal, wood wastes, agricultural wastes, kerosene etc, its environmental compatibility i.e efficient sulphur removal, low NO_x emission and high combustion efficiency. These factors led to the development of CFB steam generators. Research then began on the various aspects related with CFB.

Recently majority of the work on hydrodynamics and heat transfer characteristics were reported on a single riser of CFB unit operated under fast fluidization mode. Very few researchers have reported about hydrodynamics and heat transfer characteristics, those changes abruptly with change in dimensions (scale-up) of circular riser. Moreover, now a days' industry prefers fast fluidization with rectangular or square cross section CFB riser for power generation. Another important integral component of CFB unit is cyclone separator. Cyclone separator in the circulating fluidized bed 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 separator is small due to less residence time and insufficient oxygen. However, additional combustion of carbon monoxide and the volatiles often occur in the cyclone separator. The outer skin temperature of the cyclone separator is relatively high incurring excessive heat losses due to natural convection and radiation. Recovery of the heat has been accomplished in many cases by circulation of cool water or saturated steam to convert it into superheated steam. There is still scope to increase the capacity of the CFB boiler through extraction of heat from the cyclone

separator. From the literature review it is evident that most of the work has been completed on hydrodynamics and bed-to-wall heat transfer characteristics for a single cyclone separator.

Therefore, present work is focused to perform parametric studies and effect of scale-up on heat transfer characteristics of risers and cyclone separators of CFB. To accomplish the aim, three CFB units of same height and different dimensions of square cross section were fabricated. CFD simulations using Fluent 6.3.26 were also performed for heated portion of the riser. Effect of parameters like sand inventory, sand particle size, superficial velocity of air and also the effect of risers' cross sectional area and cyclone separators' barrel diameter on heat transfer characteristics were predicted. Numerous numbers of experiments were conducted and subsequently the empirical correlation models were also developed for the risers and cyclone separators. Hence this study will be more promising and helpful for design and fabrication of the new CFBs.

In the present work, a flow regime study was carried out on the CFB riser of cross section 0.15 m × 0.15 m. Effect of superficial velocity of air on variation of pressure drop and suspension density along the riser column was studied. Study on wall-to-bed heat transfer characteristics for risers of three different CFB units of different cross sections 0.15 m × 0.15 m, 0.20 m × 0.20 m, and 0.25 m × 0.25 m has been completed. Risers of all the CFB units are of same height 2.85 m. To accomplish the scale-up study, experiments were conducted on each CFB setup for five different non-dimensional air velocities ($U^* = 5, 5.5, 6, 6.6$ and 8) and two different weights of sand inventory per unit area of the distributor plate ($P = 1750\ N/m^2$ and $P = 3050\ N/m^2$). Sand particles with average size of 460 μm were used in all the experiments. Effect of parameter like riser cross section on the axial variation of heat transfer coefficients and off axial distribution of bed temperature was compared for all the three beds. Effect of other operating parameters like velocity of air and sand inventory on heat transfer characteristics were also predicted for individual CFB setup. The results obtained were compared with available literatures.

In individual CFB setup, effect of superficial velocity and sand inventory on distribution of bed temperature across the riser and heat transfer coefficient along the riser height was studied. In all the setups it was observed that the bed temperature decreases with increase in cross section of the riser and superficial velocity of air in the riser column, and increase with increases in sand inventory. Heat transfer coefficient increases with increase in cross section of the riser and sand inventory, and decreases with increase in superficial velocity of air.

Based on the scale-up study correlations on bed Nusselt number were obtained separately for lower splash region, middle splash region and for the portion of riser covering all regions i.e lower splash, middle splash and upper splash region. A best-fit equation having non-dimensional numbers was obtained and constants of correlation were obtained with the help of Findfit function of Mathematica 5.2. Experimental results with the prediction of correlation showing maximum rms deviation of ±11.66- 21.73%.

CFD simulations using Fluent 6.3.26 were also completed to study the effect of superficial velocity of air, particle size, sand inventory and bed cross section area on heat transfer characteristics. 3D CFD simulations were performed using the Fluent 6.3.26 on steady state wall-to-bed heat transfer characteristics of CFB riser of cross section 0.15 m × 0.15 m and height 2.85 m for heated portion (heater) of same cross section of riser and height of 0.6 m, located at 0.6 m and 1.8 m above the distributor plate which is the lower splash region and upper splash region of CFB, respectively. Further simulations on upper splash region of height 0.6 m, located at 1.8 m above the distributor plate were accomplished for risers of cross section 0.30 m × 0.30 m.

Modelling and meshing were done with Gambit software - version 2.4.6. The wall of heater was maintained at the constant heat flux q" = 1000 W/m^2. RNG k-ε model was used for turbulence modelling. Eulerian model with Gidaspow phase interaction scheme was used to simulate the two phase flow (air + sand mixture flow).

Effect of particle size on heat transfer characteristics of lower splash region was predicted using six particle sizes falling in the range of Geldart *B* type particles (60 μm, 100 μm, 160 μm, 260 μm, 360 μm, 460 μm) at sand inventory of 7 kg and superficial velocity of air as 2.5 m/s for the heater of cross section 0.15 m × 0.15 m.

Effect of superficial velocity of air and sand inventory on heat transfer characteristics was predicted with respect to lower splash region of riser of cross section 0.15 m × 0.15 m for two superficial velocities of air (2.5 m/s and 4 m/s) and two sand inventories (4 kg and 7 kg) for particle size of 460 μm.

Effect of riser cross section on heat transfer characteristics was predicted with respect to upper splash region of risers of cross section 0.15 m × 0.15 m and 0.30 m ×

0.30 m for two superficial velocities of air (2.5 m/s and 4 m/s) at 3050 N/m^2 (weight of sand inventory per unit area of distributor plate) and sand particle size of 460 μm is used during the simulation.

It is observed that bed temperature and heat transfer coefficient increases with increase in sand inventory and decreases with increase in particle size. Bed temperature and heat transfer coefficient also decreases with increase in superficial velocity of air. Bed temperature decreases and heat transfer coefficient increases with increase in cross section of risers. Results obtained from CFD simulations and experimental results obtained from available CFB setup of IIT Guwahati were in good agreement.

Heat transfer behaviour in the cylindrical portion of cyclone separators having different size of barrel diameter belonging to three different CFB units also has been studied. Steady state experiments were carried out by providing heat in the lower splash region of 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 cyclone separators) on heat transfer characteristics, experiments were conducted under similar operating conditions on three CFB setups. Cyclone separator's design ratios i.e ratios of various dimensions of cyclone separator with respect to cyclone barrel diameter were maintained same in each cyclone separator belonging to the three different CFB setups. Experiments were conducted on each CFB setup for 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 (P = 1750 N/m^2 and 3050 N/m^2).

Effect of parameters like superficial velocity of air and sand inventory on heat transfer characteristics was investigated for individual cyclone separator. 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. In all the cyclone separators, it is observed that the bed temperature decreases with increase in cyclone's 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 inventory of sand. It decreases with increase superficial velocity of air.

Based on the scale-up study, correlation on Nusselt number was obtained for cyclone separators. A best-fit equation having four non-dimensional numbers fitting 60 experimental data points was obtained and constants of the correlation was obtained with the help of Findfit function of Mathematica 5.2. Experimental results with the prediction of correlation showing maximum rms deviation of ± 14.31%.

The thesis is organised in seven chapters. Chapter 1 deals with the introduction. Chapter 2 presents the literature review and scope for the present investigations. In Chapter 3, details about the experimental setups and procedure are explained. Chapter 4 includes experimental results and discussions on parametric study and effect of scale-up on heat transfer characteristics of circulating fluidized bed risers. Chapter 5 includes computational study (modelling and simulation) using Fluent 6.3.26 on CFB risers. Chapter 6 deals with experimental results and discussions on parametric study and effect of scale-up on heat transfer characteristics of cyclone separators. Conclusions and future scope are presented in Chapter 7.