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Effect of pressure and carbon dioxide concentration on heat transfer at high temperature in a Pressurized Circulating Fluidized Bed (PCFB) combustor

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Abstract

Experiments are performed in an electrically heated 52.5 mm diameter and 2020 mm high pressurized circulating fluidized bed to investigate the bed-to-wall heat transfer in it. The bed-to-wall heat transfer is determined from the radial temperature distribution in the wall. The CO_2 content of the fluidizing gas is changed by either adding varying amounts of CO_2 to the air or by burning coal and coke with and without an addition of limestone. The heat transfer coefficient increases with both system pressure and bed temperature due to increased contribution of gas convection and radiation. The heat transfer coefficient also increases with CO_2 concentration due to increased non-luminous radiation from CO_2. © 2001 Published by Elsevier Science Ltd.

Keywords: Pressurized Circulating Fluidized Bed; Heat transfer; Gas convection; Radiation; CO_2 concentration; Temperature

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1. Introduction

The Pressurized Circulating Fluidized Bed (PCFB) combustion is a recent member of the fluidized bed combustion family. This type of circulating fluidized bed operates at elevated pressures but still maintains all the advantages of the circulating fluidized bed boiler system. This technology is relatively new and is only at the demonstration stage. PCFB boilers offer efficient and clean combustion of fuel and reduced plant size.

PCFB system has several advantages over atmospheric Circulating Fluidized Beds (CFB). They are: (1) pressurization of the boiler allows substantial reduction in the physical size of major components and auxiliary equipment for a given throughput; (2) components can be modularized and mostly factory built; (3) shop fabrication offers lower costs and shorter construction time; (4) the overall plant efficiency can be improved by the use of gas turbine and steam turbine in a combined cycle arrangement; (5) higher sulfur capture is possible in the combustor for the same Ca/S ratio due to enhanced penetration of SO_2 into the pore structure of the limestone or dolomite; (6) higher NOx reduction is possible due to the reducing effect of increased carbon concentration in the bed; (7) higher grate heat release rate than atmospheric beds is achieved due to higher mass flow rate of air per unit grate area.

As compactness is an important feature of PCFB boiler, heat transfer plays an important role in the design and operation of PCFB boilers. The bed-to-wall heat transfer depends on several operating variables. Shen et al. [1] investigated bed-to-wall convective heat transfer in a PCFB cold model, Issakson et al. [2] reported some experimental data on the overall performance of a 10 MWth PCFB pilot plant, Sellakumar and Engstrom [3] presented some details on the effect of operating parameters on the performance of a PCFB unit. Basu and Cheng [4] reported some data on the effect of bed temperature and pressure on heat transfer. A simple model for heat transfer including the effect of some operating parameters in a PCFB is reported by

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Nomenclature

d_i	inner diameter of the heat transfer section, m
d_o	outer diameter of the heat transfer section, m
h	heat transfer coefficient, W/m^2 K
k_s	thermal conductivity of the heat transfer section, W/m K
ΔP	pressure drop, Pa
R	Ca/S ratio
T_{bed}	bed temperature, K
T_{wi}	inside surface temperature of the heat transfer section, K
T_{wo}	outside surface temperature of the heat transfer section, K

Nag and Gupta [5]. However, neither this model nor the data of Basu and Cheng took account of the effect of partial pressure of CO_2 on the radiative heat transfer.

Non-luminous radiation from tri-atomic gases (CO_2, H_2O, SO_2) is an important contributor to the overall heat transfer in a combustor. So far, no information is available in the published literature on the effect of concentration of tri-atomic gases on PCFB heat transfer. As the fluidizing gas is rich in tri-atomic gases, an understanding of how the bed-to-wall heat transfer coefficient depends on operating pressures and CO_2 and H_2O concentration is very important both for boiler design and operation. This is especially true in the case of a pressurized combustor where partial pressure of non-luminous gases like CO_2 and H_2O is very high, and therefore may have an important effect. In the present investigation the effect of CO_2 concentration alone on the heat transfer coefficient is studied.

2. PCFB test rig and experimental procedure

The experimental facility consists of a PCFB unit enclosed in an electrically heated chamber (Fig. 1 shows the details of the PCFB unit). The riser is 52.5 mm in diameter and 2020 mm in height. The riser operates in fast fluidization regime during the operation. Most solids are separated in the primary cyclone and are returned to the bed through the standpipe, loop seal, and a non-mechanical recycle control valve. Gas from the primary cyclone passed through the secondary cyclone and then exited through the stack. The pressurized gas for fluidization comes from a high-pressure air compressor (up to 700 kPa). The operating pressure in the bed is adjusted with the help of a choking type control valve at the exit. The system pressure is read from pressure gauges. The bed is enclosed in an electrically heated furnace, whose temperature can be controlled. Its operating temperature is pre-set before each test.

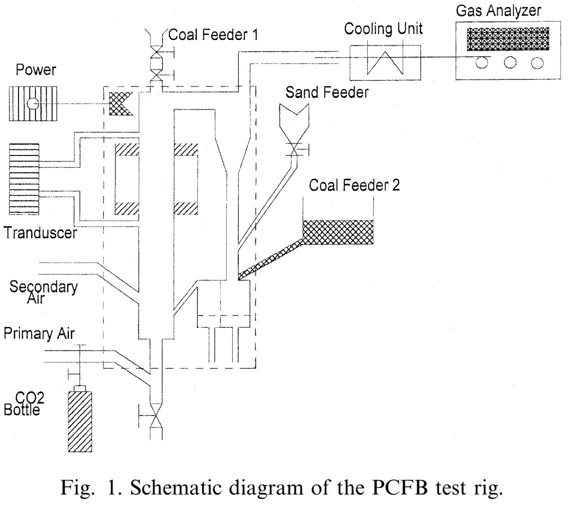
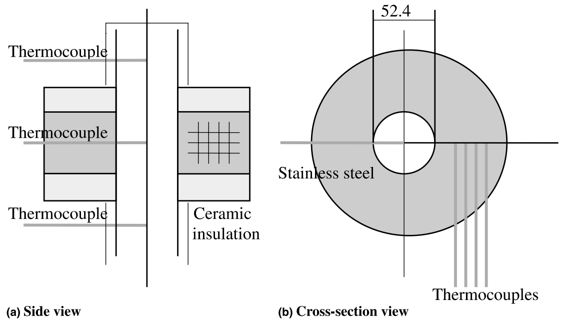


Fig. 1. Schematic diagram of the PCFB test rig.

Since the bed operates at high pressure and temperature, a special high strength and corrosion resistance material is required. The PCFB unit is made from nominal 50 mm Inconel Alloy 600 that has high strength and resistance to corrosion at high temperature. Passages for primary and secondary air are made of 316 stainless steel tubes, and the cyclone and the loop seal are made of Inconel.

Suspension density is known to be an important parameter influencing the bed-to-wall heat transfer. The pressure drop across the riser column of a CFB is due to the solid holdup within that section, Basu and Fraser [6]. So the suspension density of the bed is calculated from the static pressure drop measured along the riser height. The measurement of pressure drop in a PCFB is more difficult than that in an atmospheric CFB. A special metal filter with fine pores is installed in each pressure tap to prevent bed material from blowing out to plug the pressure measurement line. Two instruments are chosen to measure the pressure drop. One is an inclined Durblock Solid Plastic stationary gauge (Range 0–4 in. of water, Minor Scale Div., 0.02) and the other is an electronic pressure transducer, made by Auto Trans Inc. USA (range 0–5 in. WCD). To minimize the pressure difference across the wall of the transducer, the pressure transducer itself is mounted inside a vessel maintained at bed pressure.

The details of the heat transfer test section are shown in Fig. 2. The test section is heated electrically. The heat transfer section is made of stainless steel. It is located in the upper part of the bed. Its inside diameter is the same as that of the bed column. The outer diameter of the test section is 140 mm, and its height is 150 mm. Twelve K-type thermocouples are positioned at three levels with



(a) Side view (b) Cross-section view

Fig. 2. Details of the heat transfer section.

four in each level (Fig. 2). These are positioned to give the radial temperature profile of the test section. Special efforts were made to ensure that heat conduction through the test section column was one-dimensional, i.e., radial alone. For three-dimensional heat flow, the solution procedure will be complex and Eq. (1) can no longer be used. One-dimensional heat flow was achieved by minimizing the heat loss from the top and bottom extension surfaces of the heat transfer section, (Fig. 2(a)). A 30 mm layer of insulating ceramic fiber is placed both above and below to reduce any heat conduction in the vertical direction of the heat transfer section. Effectiveness of this is evident from steady-state temperatures recorded at three levels. The temperature difference between two levels at any radial distance was negligible (Fig. 3) confirming the pure radial flow of heat. So, one could write the one-dimensional heat conduction in a cylinder as

$$h = \frac{2k_s(T_{wo} - T_{wi})}{d_i(T_{wi} - T_{bed})\ln(d_o/d_i)}, \tag{1}$$

where k_s represents the thermal conductivity of the heat transfer section, T_{wi} and T_{wo} are inside and outside surface temperatures of the heat transfer section, respectively. Since no thermocouple is exactly at the inner or outer surfaces, T_{wo} and T_{wi} are calculated from a logarithmic extrapolation of the measured temperatures in the heat transfer section (Fig. 3). Here d_i is the inner diameter and d_o is the outer diameter of the test section. The bed temperature T_{bed} is measured by a thermocouple located in the center of the heat transfer section.

The PCFB was operated in two conditions. Heat transfer is measured in each of these conditions. The first series is carried out in the absence of combustion. The riser, including the test section is heated by resistance heaters located around the PCFB. Measured amounts of carbon dioxide gas is supplied to the bed externally from gas cylinders. The effect of CO_2 concentration on heat transfer coefficient is investigated for different system pressures, bed temperatures and air velocities.

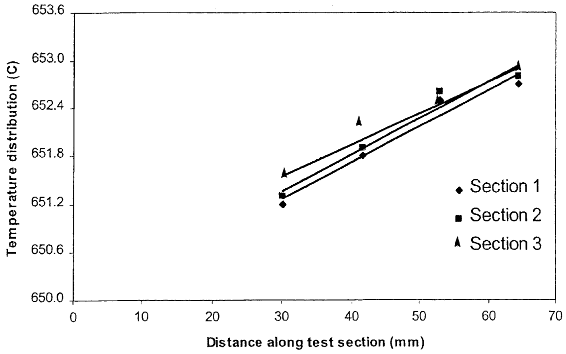


Fig. 3. Temperature distribution measured along the radial line at three levels of the wall.

In the next series, coal and/or coke are burnt in the unit. The combustion is carried out with and without the addition of limestone to simulate combustion with sulfur capture. After reaching a physical and chemical steady-state, gases leaving the combustor are continuously sampled through a probe inserted between the secondary cyclone and the heat exchanger. The concentration of CO_2, produced through combustion and calcinations of limestone, is measured by Ecom-AC microprocessor controlled portable gas analyzer.

The composition of coal and coke used in the investigation are listed in Tables 1 and 2, respectively. The operating conditions are listed in Table 3. Sand is used

Table 1
Analysis of coal and limestone

Coal	
Carbon	63.49%
Hydrogen	3.99%
Nitrogen	1.03%
Oxygen	1.84%
Sulfur	5.67%
Ash	20.3%
Moisture	2.17%
Limestone	
$CaCO_3$	89.9%

Table 2
Analysis of coke

Coke	
Carbon	89.1%
Hydrogen	0.57%
Nitrogen	1.04%
Oxygen	0.15%
Sulfur	0.71%
Ash	12.2%
Moisture	0.15%

Table 3
Operating conditions

Bed temperature	925–1125 K
Average bed density	11.1 kg/m^3 (for 2 bar) 16.19 kg/m^3 (for 4 bar) 19.21 kg/m^3 (for 6 bar)
Superficial air velocity	1, 3, 5 m/s
Ca/S ratio	1.6, 2, 2.5, 3
Overall efficiency of separators	99%

Table 4
Properties of bed material

Properties	Sand
Mean particle size, μm	245
Density, kg/m^3	2581
Bulk density, kg/m^3	1291
Minimum fluidizing velocity at 20°C and 1 bar, m/s	0.054
Terminal velocity at 20°C and 1 bar, m/s	1.87
Minimum fluidizing velocity at 227°C and 5 bar, m/s	0.038
Terminal velocity at 227°C and 5 bar, m/s	1.15

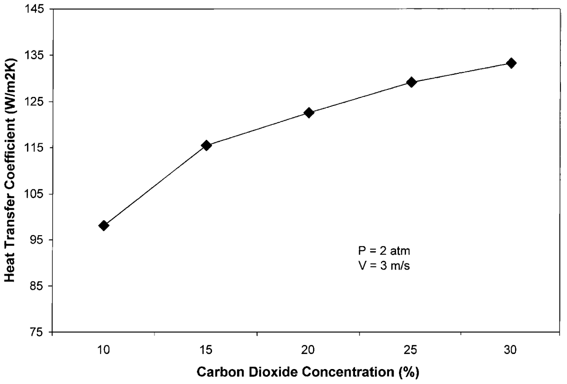


Fig. 4. Variation of heat transfer coefficients with CO_2 concentration measured in the electrically heated PCFB operated at 900 K and 2 atm pressure.

as the bed material. The relevant properties of the sand are given in Table 4.

The experiments are conducted for various operating conditions, e.g., system pressure, fluidizing velocity, CO_2 concentration and bed temperature. The results are described in Figs. 4–13.

3. Results and discussion

In the present work, experiments are conducted to study the effect of CO_2 concentration, system pressure,

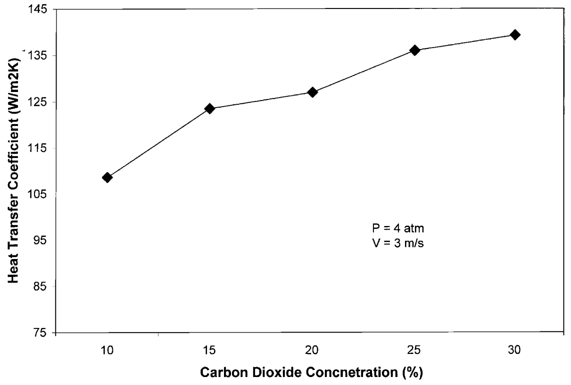


Fig. 5. Variation of heat transfer coefficients with CO_2 concentration measured in the electrically heated PCFB operated at 950 K and 4 atm pressure.

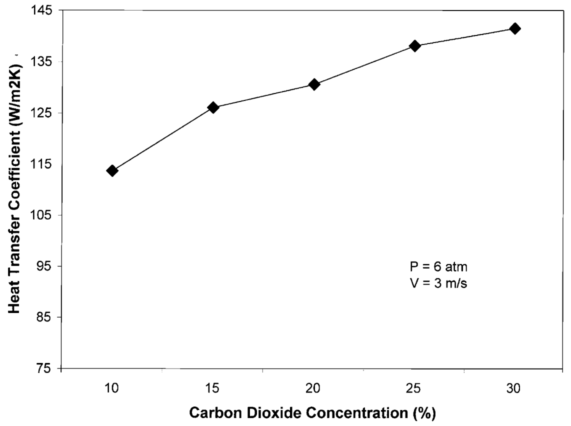


Fig. 6. Variation of heat transfer coefficients with CO_2 concentration measured in the electrically heated PCFB operated at 6 atm pressure and 973 K.

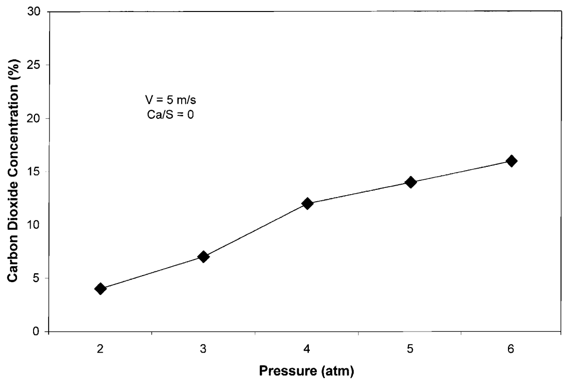


Fig. 7. Variation in CO_2 concentration with pressure measured in the coal fired PCFB at about $T_b = 1100$ K and without any limestone.

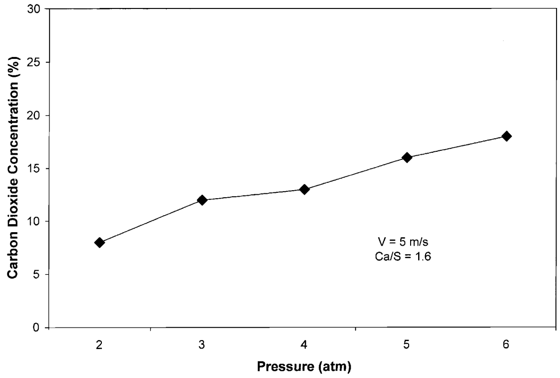


Fig. 8. Variation in CO_2 concentration with pressure measured in the PCFB at about $T_b = 1100$ K. Coal was burnt with limestone at a molar ratio (Ca/S = 1.6) at $T_b = 1100$ K, $V = 5$ m/s.

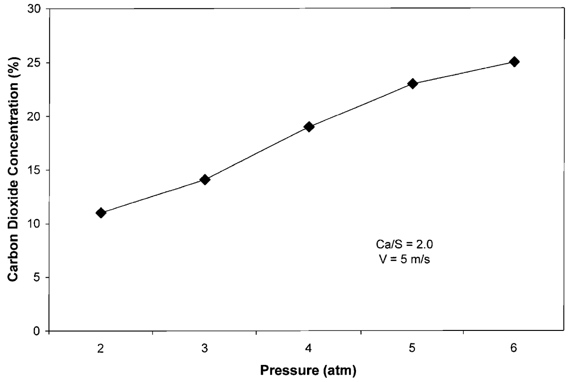


Fig. 9. Variation in CO_2 concentration with pressure measured in the PCFB at about $T_b = 1100$ K. Coal was burnt with limestone at a molar ratio (Ca/S = 2.0) at $T_b = 1100$ K, $V = 5$ m/s.

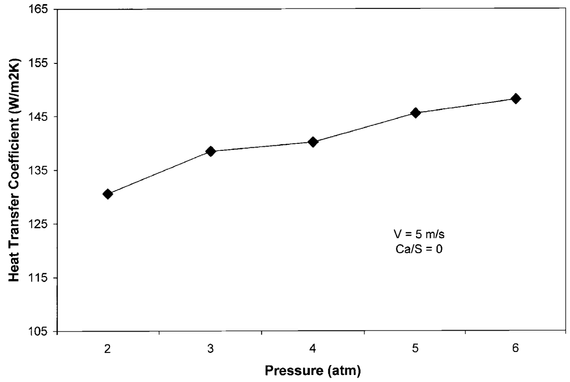


Fig. 10. Variation of heat transfer coefficient with system pressure at $T_b = 1073$ K (coal combustion without limestone).

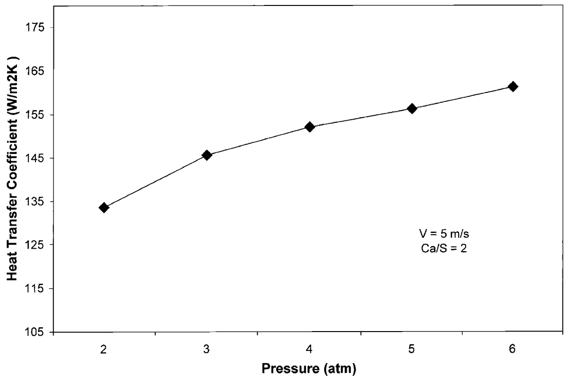


Fig. 11. Variation of heat transfer coefficient with system pressure measured in presence of coal combustion with limestone (Ca/S = 2.0) at $T_b = 1073$ K.

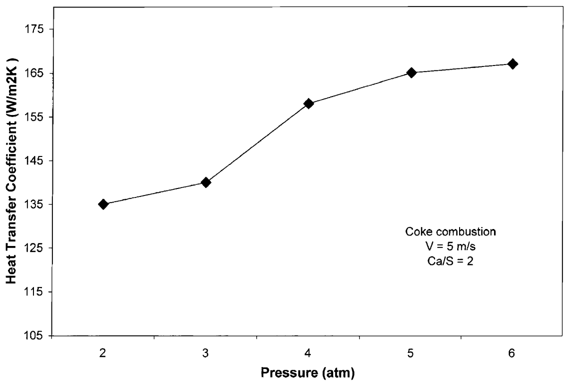


Fig. 12. Variation of heat transfer coefficient in a PCFB with system pressure measured in presence of coke burning combustion with limestone (Ca/S = 2.0) at $T_b = 1073$ K.

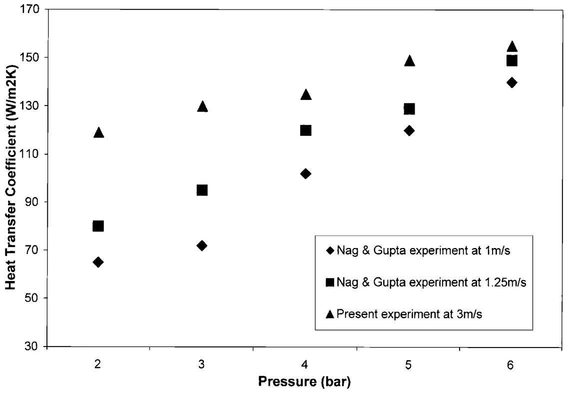


Fig. 13. Variation of heat transfer coefficient with pressure and its comparison with data from other investigators.

air velocity and bed temperature on heat transfer coefficient.

3.1. Effect of CO_2 concentration and system pressure on heat transfer coefficient in absence of combustion

The effect of volumetric concentration of CO_2 in the bed on heat transfer coefficient is shown in Figs. 4–6 for given fluidizing velocities and bed temperatures. The heat transfer coefficient increases with the increase in CO_2 concentration. At a given system pressure and bed temperature, the gas emissivity rises when the volumetric concentration of CO_2 increases. This results in higher radiative flux, and consequently higher heat transfer coefficients. The increase in gas emissivity is due to the increase in partial pressure of CO_2, which could happen either due to the increase in the total system pressure or due to the increase in volumetric concentration. The heat transfer coefficient may also increase due to increased thermal conductivity of gas-particle clusters at higher pressures.

The net effect is that in a PCFB unit the increase in CO_2 concentration at a given operating condition results in higher heat transfer coefficients. However, the mean beam length in the present test rig is much shorter than that expected in commercial boilers. Therefore, the effect of pressure on heat transfer coefficient will be much more prominent in commercial boilers. At the time of writing, the data on heat transfer in large PCFB combustors are not available in open literature, but one speculates from their design that heat transfer coefficient must be substantially larger than that in atmospheric pressure CFB combustors. The above result confirms this speculation.

3.2. Coal combustion: effect of pressure, bed temperature and air velocity on heat transfer coefficient

Coal was first burnt without the presence of limestone. At increased system pressure, the partial pressure of oxygen increased. Therefore, the reaction rate and consequently products of combustion, CO_2 increased. Fig. 7 shows the variation of measured CO_2 concentration in the bed without limestone addition for a particular bed temperature and air velocity at different system pressure.

When limestone was added to the bed at a ratio (Ca/S = 1.6), a similar increase in the CO_2 concentration with a rising system pressure was observed (Fig. 8). The result is significant because the higher pressure did not depress the calcination rate as observed in pressurized bubbling fluidized beds. This special feature will allow a PCFB to use limestone instead of expensive dolomite for sulfur capture. The measured concentration of CO_2 with limestone addition is higher (Fig. 8) than that without for the same operating conditions due to calcination of limestone $CaCO_3 \Longleftrightarrow CaO + CO_2$. Increased CO_2 concentration means increase of the partial pressure of CO_2 at a given pressure. Therefore, the gas emissivity which contributes to a higher radiation results in higher heat transfer coefficients.

The variation of CO_2 concentration in the bed with system pressure for a higher Ca/S ratio (R) ratio is shown in Fig. 9. For a particular fluidizing velocity, the CO_2 concentration in the bed increases with Ca/S ratio. Though the increase in CO_2 concentration in the bed contributes to a higher heat transfer coefficient due to increased radiation, the designer cannot choose the Ca/S ratio entirely on the basis of heat transfer. The Ca/S ratio will be selected in such a way as to minimize the limestone consumption for required level of sulfur capture.

The variation of heat transfer coefficient with system pressure in the presence of coal combustion at a given fluidizing velocity without limestone addition to the bed is shown in Fig. 10. The heat transfer coefficient increases with system pressure. This is due to increased gas density, cluster thermal conductivity, gas convection and radiation. This effect will be much more prominent in commercial PCFB boilers where the mean beam length of radiation is higher.

Fig. 11 shows the variation of heat transfer coefficient with system pressure for Ca/S = 2 and velocity 5 m/s. It shows that the heat transfer coefficient increases with the system pressure (as seen in Fig. 10 for Ca/S = 0).

Fig. 12 compares the heat transfer coefficients with system pressure for the combustor operated with Coke burning in presence of limestone (Ca/S = 2). For a given operating condition, the heat transfer coefficient is moderately increased with limestone addition. With limestone added, the heat transfer coefficient is higher due to higher CO_2 concentration in the bed, which results in higher partial pressure of CO_2. This result is not much different from that for coal burning bed (Fig. 11) suggesting that fuel type does not have any direct influence. As explained earlier, the higher partial pressure of CO_2 increases gas emissivity and radiation contribution. Also, due to the high pressure the gas density and cluster thermal conductivity increase resulting in higher heat transfer coefficients. The increase of heat transfer due to the presence of limestone is only moderate, because the non-luminous radiation from CO_2 gas depends on the product of partial pressure of the gas and its mean beam length. The present 52.5-mm diameter riser provides a very small mean beam length. Thus the resultant effect of limestone addition is very small.

Combustion conditions did not allow the maintaining of any level of CO_2 concentration in the bed. So, for a systematic study, CO_2 was added artificially from an external gas cylinder to the PCFB heated by external electrical heaters. However, the combustion test results, as seen above, have a good agreement with those obtained with the artificial addition of CO_2. So the results for non-combustion condition are valid for combustion conditions in the PCFB.

3.3. Comparison with other data

Experimental data on high temperature PCFB are scarce in the open literature. Limited data are available from the work of Basu and Cheng [4] and Nag and Gupta [5]. To bench-mark the present data, the experimental data of Nag and Gupta [5] are compared in Fig. 13 with those of present experiments. Both sets of data show similar dependence on pressure. However, their data is consistently lower than those of present experiment. Complete details of Nag and Gupta's experiment are not available. However, it is known that their riser diameter (37.5 mm) is smaller than that of the present riser and they did not add carbon dioxide into the bed. This accounts for lower non-luminous gas emissivity and therefore lower heat transfer coefficient.

4. Conclusion

1. Heat transfer coefficient increases with volumetric concentration of CO_2 in the PCFB riser.
2. Heat transfer coefficient in a PCFB increases with bed temperature due to increased convection and radiation contributions.
3. The heat transfer coefficient increases with the system pressure due to increased non-luminous gas radiation. For a given volumetric concentration of CO_2, the partial pressure of CO_2 increases with an increase in the system pressure. This increases the gas emissivity, and therefore the radiation component, which in turn, increases the overall heat transfer coefficient.
4. The heat transfer coefficient increases to a moderate extent with limestone addition due to the increased CO_2 concentration through calcination of $CaCO_3$. This increases the gas emissivity and radiation contribution resulting in higher heat transfer coefficients. This effect could be much prominent in commercial PCFB boilers where the radiative mean beam length is much greater.

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