EXPERIMENTAL STUDY OF SUSPENSION TO SURFACE HEAT TRANSFER IN A CIRCULATING FLUIDIZED BED

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***Abstract**: The purpose of this research was the experimental study of suspension to surface heat transfer in a pilot scale circulating fluidized bed system. A Rotational Composite Central Design of experiments was applied in order to identify the influence of three important factors: bed temperature, gas fluidization velocity and solids inventory on suspension to surface heat transfer coefficient. Experiments were done using quartz sand, 356 μm mean diameter as solid material and air as fluidization gas. A total of eighteen tests were performed for five riser temperatures (250 to 400°C), five gas fluidization velocities (5 to 7m/s) and five solids inventory (7 to 9 Kg). The experimental system is composed mainly by a riser presenting 102 mm in internal diameter and 4 m in height and a 63 mm in internal diameter downcomer, a cyclone and an L-valve as recirculation solid particles device. The studied heat exchanger, double pipe type, is located in the riser; at 1000 mm above the gas entrance and presents cooling water flow through a 47.3 mm annular space, 240 mm in height. Experimental results showed that the riser temperature and the solids inventory were the greater influence factors on the suspension to surface heat transfer coefficient, while the superficial gas velocity had a weak influence on the studied phenomenon. The experimental results were compared against three theoretical models; it was observed that BASU (1989) model presented the best agreement with experimental data. A simple correlation was proposed to calculate the suspension to surface heat transfer coefficient as a function of the three studied influence factors.*

***Keywords:** circulating fluidized bed, suspension to surface heat transfer coefficient, bed temperature, solids inventory, superficial gas velocity.*

1. INTRODUCTION

Studies involving the heat transfer process in circulating fluidized beds (CFBs) have been based on the understanding of hydrodynamic behavior of the gas-solid suspension near the combustor surface. Grace (1997) reported that the heat in a CFB combustor can be transferred by several different mechanisms. Once the hot particles or clusters, at the riser core temperature, touch the wall, there will be heat transfer between particles and the cold surface while they are in contact. If the particles have a short contact time with the wall, most of the heat will be transferred by the gas layer between the particles and the surface. Nevertheless, the particles motion from the core to the riser wall is the primary means of heat transfer and the overall process is called particle convection. For the wall area uncovered by the particles, the heat transfer surface is contacting the gas or a very dilute gas-particle mixture bringing about a heat transfer mechanism termed gas convection. At high temperatures radiation heat transfer is an important factor to be considered and increases the heat transfer due to clusters and particles to both uncovered and covered surface.

Heat transfer in a circulating fluidized bed (CFB) has been studied since 1949, with the Mickley and Trilling (1949) research. Since then, research in this area has been developed successfully including experimental and more recently modeling works. The published literature review about the heat transfer process in CFBs has shown that particle diameter, suspension density, superficial gas velocity, bed temperature and solids net circulation flux (or solids entrainment flux) are important factors to be considered. Researchers as Wu et al (1987) found that the heat transfer coefficient was strongly affected by suspension density, while the superficial gas velocity, bed temperature and secondary to primary air mass flow ratio had weak influence on the suspension-wall heat transfer coefficient. Other researchers as Han and Cho (1998) studied the contribution of radiation heat transfer to total heat flux. They found that this contribution was 15 to 36 % at the operating temperature range from 650 to 850°C. Han et al (2002) found that the contribution of the radiation heat transfer was 55 to 40 % for a bed temperature range of 450 to 550 °C. Besides this works, researchers as Wu et al (1989), Wu et al (1991), Luan et al (1999) and Pagliuso et al (2000) developed experimental studies in order to obtain the heat transfer coefficient in circulating fluidized beds. Several models have been proposed based on correlations and experimental results, as the works published by Subbarao e Basu (1986), Basu (1990), Reddy (2003), Xie et al (2003a), Xie et al (2003b), Chen et al (2005) and Vijay and Reddy (2005).

This research intends to study of the effects of three different variables on the suspension to surface heat transfer coefficient: bed temperature, solids inventory and superficial gas velocity at the riser. The bed temperature range studied was 250 to 400 °C, the solids inventory range was 7 to 9 Kg, and superficial gas velocity range was 5 to 7 m/s. A total of eighteen tests were performed with quartz sand presenting *356 μm* mean Sauter diameter. This work can be used as a first approximation of the heat transfer coefficient in a circulating fluidized bed and intends to contribute for the knowledge of the process in such systems and for the riser heat exchanger design.

2. EXPERIMENTAL

2.1 Experimental equipment and test procedure

Figure 1 shows a schematic diagram of the experimental set-up. The pilot scale CFB system was made of stainless steel 310 and it is composed by a riser presenting 100 mm in internal diameter and 4 m in height, a 63 mm internal diameter and 1.9 height downcomer, a cyclone, a solids sampling valve, a solids feeding device and an L-valve 63 mm in internal diameter for solids circulation.

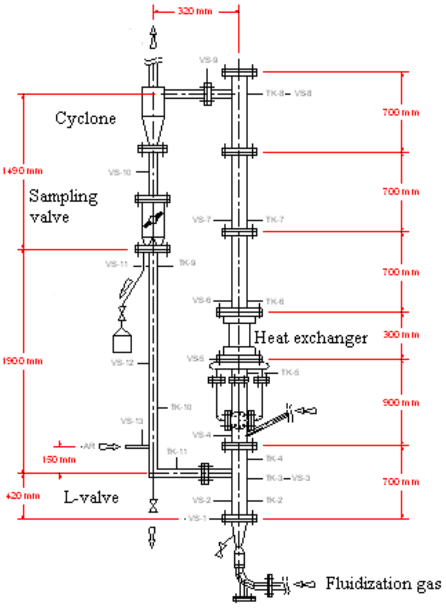

Figure 1. Schematic diagram of the experimental set-up. (Ramirez, 2007)

The parallel flow heat exchanger used to study the heat transfer process in the riser of a pilot scale CFB system was built as a double pipe with cooling water flowing in a 47,3 mm annular space presenting 240 mm in height. Figure 2 shows a schematic diagram of the heat exchanger used in this research.

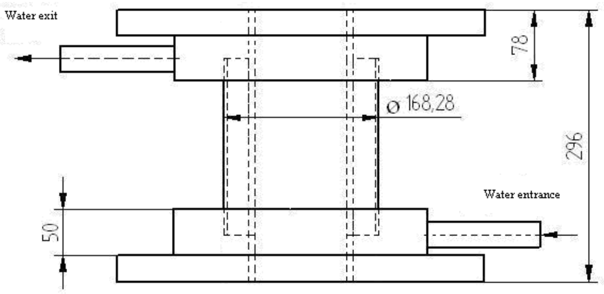

Figure 2. Schematic diagram of the parallel flow heat exchanger.

A roots air blower provided the air flow into the circulating fluidized bed system. This air flow was heated until the required temperature and the air mass flow was measured with an orifice plate meter. The air flow to the L-valve device was supplied by a compressor to provide the required solids circulation to the riser. The riser and downcomer were instrumented with thermocouples type K and pressure taps to measure the suspension temperatures and bed pressure, respectively. The cooling water temperatures were measured at the entrance and at the exit of the heat exchanger with PT-100 resistance temperature detectors. Measurements were performed in the steady state regime at the required bed temperature.

Suspension to surface heat transfer coefficient was calculated with a correlation established by Eq. (1):

$$h_b = \left[\frac{A_{t,i} DMLT}{\dot{m}_w c \left(T_{w,e} - T_{w,en}\right)} - \frac{A_{t,i}}{A_{t,o} h_w} - \frac{A_{t,i} \ln\left({A_{t,o}}/{A_{t,i}} \right)}{2\pi L k_t} \right]^{-1} \tag{1}$$

Cheremisinoff (1986) considered that the transition from laminar to turbulent flow inside an annular space begins at Reynolds number 2100 when the hydraulic diameter is chosen as the characteristic dimension. The Reynolds number's values found in this research were in the range from 145 to 218, showing that the water flow was laminar in the concentric annular duct. The Manohar (1965) criterion was chosen to establish the hydrodynamic entry length (L_{hy}) in order to verify the fully developed laminar region in the annular space. To calculate the water heat transfer coefficient it was used the Chen et al (1946) correlation which can be applied for laminar flow with Reynolds number range from 200 to 2000 with an average deviation of $\pm 6{,}6\%$. Furthermore, this correlation was developed in a concentric annular duct with isothermal internal surface and adiabatic outlet surface.

The hydrodynamic parameters in the CFB system as bed voidage and suspension density were calculated by Eq. (2) and (3).

$$\varepsilon_b = 1 - \frac{\Delta P_b}{\rho_p g L} \tag{2}$$

$$\rho_b = \frac{\Delta P_b}{gL} = \left(1 - \varepsilon_b\right)\rho_p \tag{3}$$

2.2 Experimental design

In this research a rotational composite central experimental design was applied in order to identify the influence of bed temperature, solids inventory and superficial gas velocity on the suspension-wall heat transfer coefficient. Table 1 shows the operational conditions for the designed seventeen tests performed in the pilot scale CFB system plus one additional test (number 18) utilized to verify the model proposed in this work. The experimental design was made for three central points (tests 15, 16 and 17) for experimental error calculation.

Table 1. Experimental conditions for the tests performed in the pilot scale CFB system
Real values (coding values)

Test	$T_L(°C)$	$I_p(Kg)$	$V_s(m/s)$
1	280 (-1)	7,4 (-1)	5,4 (-1)
2	370 (1)	7,4 (-1)	5,4 (-1)
3	280 (-1)	8,6 (1)	5,4 (-1)
4	370 (1)	8,6 (1)	5,4 (-1)
5	280 (-1)	7,4 (-1)	6,6 (1)
6	370 (1)	7,4 (-1)	6,6 (1)
7	280 (-1)	8,6 (1)	6,6 (1)
8	370 (1)	8,6 (1)	6,6 (1)
9	250 (-1,68)	8 (0)	6 (0)
10	400 (1,68)	8 (0)	6 (0)
11	325 (0)	7 (-1,68)	6 (0)
12	325 (0)	9 (1,68)	6 (0)
13	325 (0)	8 (0)	5 (-1,68)
14	325 (0)	8 (0)	7 (1,68)
15	325 (0)	8 (0)	6 (0)
16	325 (0)	8 (0)	6 (0)
17	325 (0)	8 (0)	6 (0)
18*	250 (-1,68)	8 (0)	5,57 (-0,67)

* This test isn't included in the experimental design

3. RESULTS AND ANALYSIS

Table 2 shows the experimental results obtained for suspension to surface heat transfer coefficient, bed voidage and suspension density for the eighteen tests performed in the circulating fluidized bed system.

Table 2. Experimental results for the tests performed in the pilot scale CFB system

Teste	ε_b	$\rho_b\left(Kg/m^3\right)$	h_b $\left(W/m^2K\right)$
1	0.985	36.9	90.2
2	0.985	36.6	162.6
3	0.9722	68.6	133.6
4	0.9774	55.8	125.8
5	0.9963	9.2	88.5
6	0.9924	18.7	127.0
7	0.99	23.7	94.6
8	0.978	52.4	139.0
9	0.988	29.0	88.1
10	0.982	44.7	101.9
11	0.983	42.1	57.8
12	0.9785	52.9	124.7
13	0.98	48.0	102.5
14	0.9864	33.6	120.5
15	0.9838	39.9	93.5
16	0.9804	48.3	100.3
17	0.9818	44.8	98.9
18*	0.9878	30.0	98.9

* This test isn't included in the experimental design

Bed temperature effect

The bed temperature effect in suspension to surface heat transfer coefficient for a solids inventory range of 7.4 to 8 Kg and a superficial gas velocity range of 5.4 to 6.6 m/s is shown in Fig. 3. It can be observed than an increase in bed temperature produced an increase on suspension to surface heat transfer coefficient values. This fact can be explained by the increase on particle convection heat transfer, while the gas convection heat transfer and radiation heat transfer had a small contribution. An increase on gas thermal conductivity and cluster thermal conductivity produce a decrease on cluster heat transfer resistance and gas layer heat transfer resistance. Other researchers as Han et al (1996), Luan et al (1999) and Reddy (2003) found similar effects for the bed temperature influence on suspension to surface heat transfer coefficient, as it was found in this research.

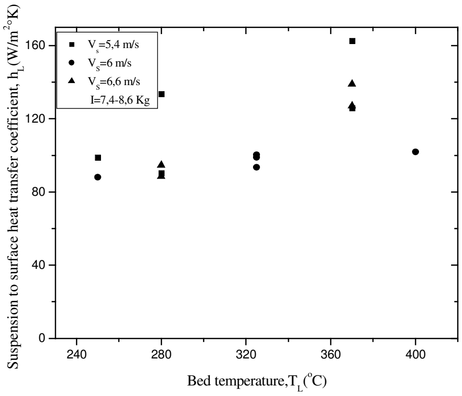

Figure 3. Bed temperature effect in suspension to surface heat transfer coefficient

Solids inventory effect

Figure 4 shows the solids inventory effect in suspension to surface heat transfer coefficient for bed temperature range from 250 to 400°C and a superficial gas velocity range from 6 to 6.6 m/s. It can be observed that the suspension to surface heat transfer coefficient is strongly influenced by the solids inventory. It was concluded that the solids inventory affects the suspension density, bed voidage, the fraction of the wall exposed to clusters (f) and the gas layer between cluster and wall (δ), therefore it influences the overall heat transfer coefficient. An increases of solids inventory produces an augment on solids concentration; this effect decreases the gas layer thickness (δ) and increases the fraction of the wall exposed to clusters (f), raising the particle convection heat transfer coefficient. This results agree with that published by researchers as Wu et al (1987), Wu et al (1989), Wu et al (1990), Han et al (1996) and Pagliuso et al (2000).

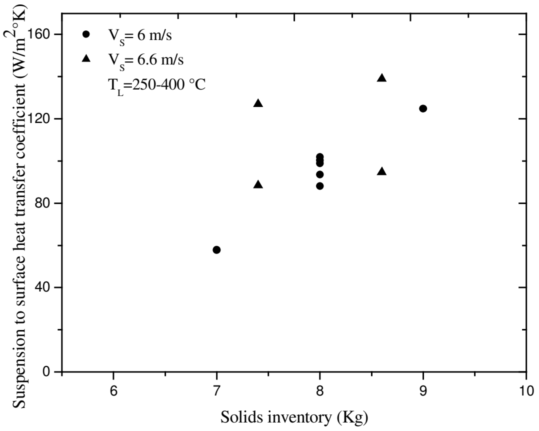

Figure 4. Solids inventory effect in suspension to surface heat transfer coefficient

Superficial gas velocity effect

The superficial gas velocity effect in suspension to surface heat transfer coefficient is showed in Fig. 5 for a solids inventory range from 7.4 to 8 Kg and bed temperature range from 250 to 325°C. It was observed that the superficial gas velocity had a weak influence on the heat transfer coefficient. An increase in superficial gas velocity decreases the heat transfer coefficient because the bed voidage augments and the solids concentration decreases. This effect increases the gas convection heat transfer coefficient and it decreases the particle convection heat transfer. Although the gas convection heat transfer coefficient increases, this effect is important only for dilute phase conditions, showing that the particle convection heat transfer is the more important contribution to the suspension to surface heat transfer coefficient for dense phase conditions. Similar conclusions were obtained by Wu et al (1987) and Ebert et al (1993).

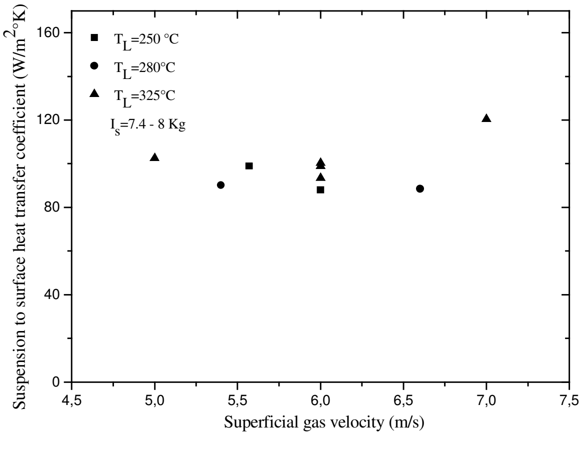

Figure 5. Superficial gas velocity effect in suspension to surface heat transfer coefficient

3.1 Theoretical models application for the present experimental conditions

The models published by Subbarao and Basu (1986), Basu (1989) and Vijay and Reddy (2005) were chosen to obtain the heat transfer coefficient for the experimental conditions of this work, comparing these values with the experimental results. It was concluded that the best agreement was obtained for the Basu (1989) model, showing a deviation range from 1 to 30 %. Figure 6 shows a comparison between experimental results and results obtained from Basu (1989) model.

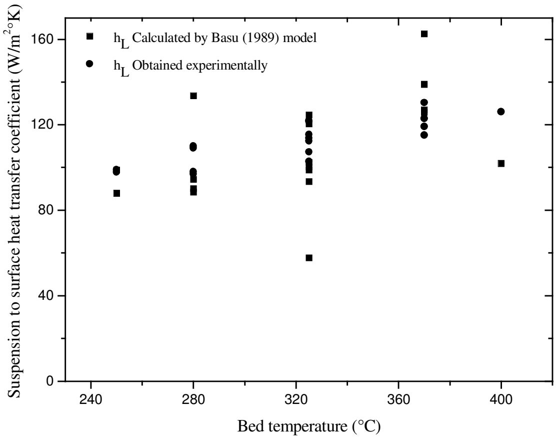

Figure 6. Comparison between experimental results and results obtained from Basu (1989) model

The Subbarao and Basu (1986) model showed smaller results, while Vijay and Reddy (2005) model calculated higher results than the obtained by the present work. The better agreement of Basu (1989) model with the experimental results could be explained by the correlation chosen to calculate the fraction of the wall exposed to clusters (f). This parameter defines the contribution of the particle convection, gas convection, and radiation in overall heat transfer coefficient. For Basu (1989) model, the values of the parameter (f) were between 0.24 and 0.38, while for Vijay and Reddy (2005) model this range was between 0.57 and 0.93. The Chen et al (2005) correlation was used in order to obtain the value for the parameter (f) concerning the experimental operation conditions and it was found values between 0.11 and 0.58, showing that only a small fraction of the wall was exposed to clusters.

3.2 Heat transfer correlation

Considering the relationship between the suspension to surface heat transfer coefficient, bed temperature, solids inventory and superficial gas velocity it is proposed a correlation to calculate the heat transfer coefficient for the operational conditions studied in this research. The correlation is given by Eq. (4) which presents a coefficient of determination equal to 0,54.

$$h_b = 96{,}23 + 12{,}5T_b + 3{,}7T_b^2 + 10{,}04I_s + 2{,}38I_s^2 - 2{,}4V_s + 9{,}54V_s^2 - 9{,}28T_bI_s + 2{,}29T_bV_s + 1{,}44I_sV_s \tag{4}$$

This correlation can be applied for the following operational conditions:

$7 \le I_s \le 9Kg$
$5 \le V_s \le 7\,m/s$
$250 \le T_b \le 400^\circ C$

In order to verify the proposed correlation, it was calculated the heat transfer coefficient for the operational conditions of the test number 18. Comparing the values obtained for both experimental and predict by Eq.(4), it was concluded that the proposed correlation presents a good agreement with the experimental results; nevertheless, it must be considered that the adjustment of the experimental results to the model was 54%. This low value indicates de necessity of additional tests for the same operational conditions.

4. CONCLUSION

A study of suspension to surface heat transfer coefficient was developed in a pilot scale CFB system with quartz sand particles of $356\mu m$ mean diameter. Eighteen tests were performed with operational conditions defined by the rotational central composite experimental design. It was studied the influence of the bed temperature (250 to 400° C), the solids inventory (7 to 8 Kg) and the superficial gas velocity (5 to 7 m/s) in the heat transfer coefficient. It was concluded that the bed temperature and the solids inventory are important factors to be considered on the process, while the superficial gas velocity had a weak influence in the coefficient. The experimental results were compared with the theoretical results calculated by three different researchers, finding the best agreement with the Basu (1989) model. The deviation of results obtained by the Basu (1989) model respect to the experimental results was 1 to 30 %.

A heat transfer correlation was proposed to calculate the suspension to surface heat transfer coefficient in CFB systems which showed a good agreement with the heat transfer coefficient obtained experimentally for the additional test number 18.

5. ACKNOWLEDGEMENTS

The authors are grateful to CAPES concerning the student scholar ships and to CNPq (process 485138/2007-7) for the financial support.

NOMENCLATURE

$A_{t,i}, A_{t,o}$	internal and outlet heat transfer area	$[m^2]$
c	water specific heat	$[J.Kg^{-1}K^{-1}]$
$DMLT$	logarithmic mean temperature difference	[-]
f	fraction of wall exposed to cluster	[-]
g	gravitational acceleration	$[ms^{-2}]$
h_b, h_w	suspension to surface heat transfer coefficient and water heat transfer coefficient, respectively	$[Wm^{-2}K^{-1}]$
I_p	solids inventory	[Kg]
k_t	tube wall thermal conductivity	$[Wm^{-1}K^{-1}]$
L	heat exchanger vertical length	[m]
$\dot{m}_w$	water mass flow rate	$[Kgs^{-1}]$
T_b	bed temperature	[K]
$T_{w,en}, T_{w,e}$	entrance water temperature and exit water temperature, respectively	[K]
V_s	superficial gas velocity	$[ms^{-1}]$
δ	gas layer between the cluster and the wall	[-]
ε_b	bed voidage	[-]
ρ_b, ρ_p	suspension density and particle density, respectively	$[ms^{-3}]$
ΔP_b	suspension pressure drop along the heat exchanger	[Pa]

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