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ABSTRACT

This paper presents a review of correlations for the heat transfer in a fluidised bed combustor (FBC). The predominant mechanisms of heat transfer for low temperature, (convection and conduction) are discussed from a physical point of view for each correlation. The magnitude of the radiative component, which is not included in most correlations reported in the literature is analysed.

The correlations were included in a fluidised bed combustor model [1] and the performance of the different correlations was assessed for two medium size reactor (0.2 MW; 2 MW) using bed particles of 2 and 1 mm, respectively.

NOMENCLATURE

Ar = Archimedes number = $\frac{\rho_p}{\rho_g} \frac{g\, d_p^3}{\nu^2}$
C_g = Specific heat capacity of gases
C_p = Specific heat capacity of bed particles
d_p = Diameter of bed particle
D_T = Diameter of tube
g = Acceleration of gravity
h = Heat transfer coefficient
h_{bc} = Bubble contribution to the convection component of h
h_{cc} = Conduction-convection component of h
h_{ic} = Intersticial gas contribution of the convection component of h
h_{pc} = Conduction component of h
h_r = Radiative component of h
K_g = Thermal conductibility of gases
Nu = Nusselt number based on particle diameter $Nu = h_{cc}\, d_p/K_g$
Nu_T = Nusselt number based on tube diameter $Nu_T = h_{cc}\, D_T/K_g$
P_h = Horizontal pitch
Pr = Prandtl number
Re = Reynolds number of particles = Ud_p/ν

Re_{mf} = Reynolds number for minimum fluidisation = $U_{mf} d_p/\nu$
Re_T = Reynolds number of tubes = UD_T/ν
T = Bed temperature
T_s = Temperature of heat transfer surface
U = Superficial velocity
U_{mf} = Superficial gas velocity at incipient fluidisation

Greek Symbols

α_g = Thermal diffusivity of gases
β = Time fraction that bubbles are in contact with the tube
ε = Bulk bed void fraction
ε_B = Bubble fraction
ε_b = Bed emissivity
ε_{ef} = Effective emissivity
ε_s = Heat transfer surface emissivity
ν = Kinematic viscosity of gases
ρ_g = Gas density
ρ_p = Bed material density
σ = Steffan Boltzmann constant

1. INTRODUCTION

Fluidised bed combustion is now generally recognized as a clean and inexpensive method for coal combustion, capable of efficiently burning a wide variety of solid fuels in an environmentally acceptable manner. Research on fluidised bed combustors (FBC) has proceeded for a number of years. In the 1970's the demand for theoretical models became urgent as the technique developed towards commercial applications. At present several mathematical models are available, although they still rely on empirical and semi-empirical expressions obtained from experiments, often under narrow parameters ranges and for cold models.

Due to the narrow temperature range used in FBC it is essential to predict the heat transfer coefficient accurately for the selection of appropriate heat transfer tube surface for specific conditions. The prediction of the FBC behaviour when the operating conditions are changed is also relevant.

Theories to explain the mechanisms of heat transfer in a fluidised bed have been proposed. However quantitative predictions using these theories are not yet possible for practical applications. The calculation of the heat transfer coefficient would require the knowledge of residence time distributions of solids in contact with immersed tube surfaces. This calculation is not possible at present for practical situations in fluidised bed combustors. The heat transfer coefficient calculation relies on empirical and semi-empirical correlations obtained mostly for cold conditions. However, the relevant parameters and their influence on the heat transfer coefficient in these correlations are often dictated by the theory.

Some of the existing models for the simulation of FBC impose the heat transfer coefficient [1, 2] while others [3, 4, 5] use experimental correlations for the heat transfer coefficient. As the experimental correlations were obtained for cold conditions a radiative component should be added [3, 5]. The correlation of Andeen and Glicksman [6] which is limited to small particle diameters is used by Louis and Tung [3] while Souza-Santos [5] uses the correlation of Xavier and Davidson [7] which was deduced for slug flows. Preto [4] developed it's own correlation from results obtained in a fluidised bed using large particles and high velocities [8].

In the present paper, the three components of heat transfer, conduction, convection and radiation, are discussed and correlations for the heat transfer coefficient are reviewed and analysed. Most of the correlations were obtained for cold models and thus do not include a radiative component. Emphasis is given to the magnitude of the radiative component which is added to the conduction-convection correlation. The objective of this work is to discuss the applicability of existing heat transfer correlations and the prime heat transfer mechanism included in each correlation. The correlations were included in a mathematical model [1] and their performance was assessed for two medium size reactors (0.2 MW; 2 MW) using bed particles of 2 and 1 mm respectively. The operating conditions of the reactors correspond to test nº 6 of the National Coal Board-Coal Research Establishment and test nº 26 Babcock-Wilcox. The experimental conditions and results were taken from Souza-Santos [5].

2. HEAT TRANSFER MODELLING

The heat transfer between the bulk of the bed and immersed surfaces can be conceived as the result of three components: i) conduction (unsteady mechanism) associated with convection of particles, ii) convection of the gas and iii) radiation. In the last two components the emulsion and bubble contribution should be considered.

2.1 *Conduction and Convection*

The relative magnitude of each of the heat transfer components depend on particle size and gas velocity. The heat transfer coefficient due to the conduction and convection components may be expressed by:

$$h_{cc} = h_{pc}(1 - \beta) + \left[h_{ic}(1 - \beta) + h_{bc}\beta\right] \tag{1}$$

where β represents the fraction of bubbles in contact with the tubes.

The term h_{pc} represents the conduction associated with particle convection which consists on the heat transfer associated with particle exchange between the bulk of the bed and the region adjacent to the heat transfer surface. This mechanism arises for gas flow rates above the minimum fluidisation when bubbles are formed promoting the motion of solids. For the particle sizes of interest to FBC the component of unsteady conduction decreases with particle size due to the reduction of the number of particles in contact with the surface. This is because the heat transfer from the particles to the surface is processed mainly through a thin gas film near the points of contact. As a consequence, for large particles the interstitial gas convection contribution (h_{ic}) becomes important. When bubbles come into contact with the heat transfer surface the heat is transferred by convection (h_{bc}). This mechanism produces a heat transfer coefficient smaller than the previous unsteady conduction mechanism. This fact is responsible for the decrease of the heat transfer coefficient when the gas flow is increased beyond a certain optimized situation.

As a result of the conduction and convection mechanisms the maximum heat transfer coefficient initially decrease with particle size increasing again for large particle sizes. The transition occurs for particle diameters of 1 to 2 mm. Decreasing temperature and increasing pressure, the convective term is increased due to the larger density of the gases.

The configuration and dimensions of the cooling coil can promote a reduction up to 10% on the heat transfer coefficient as long as some basic design rules are considered, [9, 10]. The choice of the tubes orientation is dependent mainly on constructive and erosion conditions. The heat transfer coefficient for vertical tubes is only about 5% higher than for horizontal tubes. In accordance with several authors [11] for tube diameters smaller than 10 mm (wires) the heat transfer coefficient increases due to the higher renewal rate of particles near the tubes. This effect is notorious for diameters smaller than 3 mm. For diameters larger than 20 mm the influence of the tube diameter on the heat transfer coefficient decreases.

Following the basic theory principles, the selected heat transfer correlations are analysed and discussed. The selected correlations are summarized in Table 1. Table 2 presents the, dependence of the heat transfer coefficient on gas velocity, particle size and tube diameter. The range of experimental conditions is presented in order to show the region of applicability of the correlations.

Except for the cases of Vreedenberg [12] and Preto [8], all correlations consider a measure of the fraction of time that the particles are in contact with the tubes $(1 - \beta)$. The inclusion of this parameter, allows the prediction of the maximum in the heat transfer coefficient when the gas velocity increases. The value of the factor β is usually taken from the bubble fraction ε_B or from the bulk voidage ε. Glicksmann and Decker [13] introduce a factor of 5/6 in the bubble fraction in contact with the tubes to account for the fact that bubble fraction near heat transfer surfaces is smaller than the average. Catipovic et al. [14] obtained the fraction $(1 - \beta)$ from an experimental correlation and Grewal [9] adapted the same procedure for the bulk porosity [15].

From the correlations analysed here, only the correlation of Catipovic *et al.* [14] includes the contribution of the convective term due to the passage of the bubbles in contact with the surface (h_{bc}) whose contribution is small.

All correlations contain a term corresponding to the unsteady conduction mechanism, (h_{pc}). This term is approximately inversely proportional to the particle diameter. For small particles and large contact periods, the properties of the bed material are important for the conduction component. This component depends on the thermal properties of the solids in particular on the heat capacity of the particles which is only included in the correlation of Grewal [9]. None of the correlation include the influence of the bed conductivity. For large particles the unsteady conduction component is controlled by the conduction of heat through a gas film layer of assumed thickness between $d_p/6$ [10, 14] and $d_p/10$ [13].

The interstitial convection component (h_{ic}) of heat transfer is included in the correlations [10, 13, 14] developed with particle sizes above 1 mm in diameter. This heat transfer component increases with both the particle diameter and/or the gas velocity (see table 2). The influence of these two parameters is differently expressed in the correlations showing the uncertainty still existing. Glicksman and Decker [13] introduce the influence of gas velocity on the convective component through a correlation obtained in a fixed bed. Catipovic *et al.* [14] adopted a correlation for the convective component based on the minimum fluidisation conditions. This explains the appearance of the Archimedes number

AUTHOR	CORRELATION
Vreedenberg (1958)	$Nu_T = 420 \left[\frac{Re_T}{Ar}\right]^{0.3} Pr^{0.3}$ for $\frac{\rho_p}{\rho_g} Re_T > 2500$
Andeen and Glicksmann (1976)	$Nu_T = 900 \left(1 - \varepsilon\right) \left(\frac{Re_T}{Ar}\right)^{0.326} Pr^{0.3}$
Glicksmann and Decker (1980)	$Nu = \frac{5}{6} \left(1 - \varepsilon_B\right) \left(11.2 + 0.05 \; Re \; mf \; Pr\right)$
Catipovic et al. (1980)	$Nu = \left(1 - \beta\right) \left(6 + 0.0175 \; Ar^{0.46} \; Pr^{0.33}\right) +$ $+ \frac{d_p}{D_T} \left(0.88 \; Re_{mf_T}^{0.5} + 0.0042 \; Re_{mf_T}\right) Pr^{0.33} \beta$ $\left(1 - \beta\right) = 0.45 + \frac{0.061}{\left(U - U_{mf}\right) + 0.125}$
Zabrodsky et al. (1981)	$Nu = 6 \left(1 - \varepsilon\right) \frac{1.2}{\left(1 - \varepsilon\right)^{\frac{1}{3}}} + B \; U^{0.2} \frac{d_p^2}{\alpha_g} \; ; \; B = 26.6 \; m^{-0.2} s^{-0.8}$
Grewal (1981)	$Nu_T = 47 \left(1 - \varepsilon\right) \left(\frac{Re_T}{Ar}\right)^{0.325}$ $x \left(\frac{r_p \, C_p \, D_T^{3/2} \, g^{1/2}}{K_g}\right)^{0.23} Pr^{0.3} \left(1 - 0.21 \left(\frac{p_h}{D_T}\right)^{-1.75}\right)$ $\varepsilon = \left(\frac{18 \; Re + 0.36 \; Re^2}{Ar}\right)^{0.21}$
Preto (1986)	$Nu = 0.6 \; Ar^{0.246}$

$A_r = \frac{d_p^3 \rho_g \rho_p g}{N^2}$ $\quad$ $Re_T = \frac{v}{\nu} D_T$ $\quad$ $Re = \frac{v}{\nu} d_p$ $\quad$ $\alpha_g = \frac{Kg}{C_g l_g}$

Table 1. — Correlations for the Conduction - Convection Component of the Heat Transfer Coefficient

	Vreedenberg (1958)	Andeen and Glicksmann (1976)	Glicksmann and Decker (1980)	Catipovic et al. (1980)	Zabrodsky et al. (1981)	Grewal (1981)	Preto (1986)
Dependence h_{cc} - U^x							
Conduction	0.3	0.326	0	0	0	0.325	
Convection	---	---	1	0	0.2	---	0
Dependence h_{cc} d_p^x							
Conduction	- 0.9	- 0.978	- 1	- 1	- 1	- 0.975	- 0.26
Convection	---	---	0	0.38	1	---	
Dependence h_{cc} D_T^x	- 0.7	- 0.674	---	---	---	- 0.33	---
Experimental conditions tested							
Particle diameter (range mm)	0.13 - 0.35	0.36 - 0.81	0.65 - 2.85	1.3 - 4.0	2.0 - 3.0	0.17 - 0.50	0.15 - 2.0
Particle density ($g\ cm^{-3}$)	2.17; 5.21	2.5	Dolomite	Dolomite	1; 2.3	2.7; 4	1.3 - 2.6
Superficial gas velocity ($m\ s^{-1}$)	< .15	0.3 - 1.9	0.5 - 3.5	> 1.2 U_{mf}	.6 - 2.8	> 1.3 U_{mf}	< 5,5 U_{mf}
Tube diameter (mm)	16.9 - 51	19		> 20	30	12.7; 28.6	21.3
Ratio p_h/D_T	---	2		> 2	1.5 - 3.3	1.7 - 9	

Table 2 — Influence of parameters on the Heat Transfer Correlations

which increases with minimum fluidisation velocity. Zabrodsky *et al.* [10] developed an empirical correlation in which the thermal diffusivity of the gases was introduced. However the correlation uses a dimensional constant which can hide physical information.

The influence of the tube diameter D_T on the heat transfer coefficient is different for small and large particles, due to the relative importance of the conduction and convection components. For large particles the correlations for the heat transfer coefficient are independent of tube diameter except for the bubble convection term [14]. For small particles the correlations use the tube diameter as the characteristic dimension for the Nusselt number and thus the heat transfer coefficient depends inversely on the tube diameter. The use of the tube diameter suggest the importance of the hydrodynamics around the tubes for the particle convection mechanism. In the correlation of Grewal [9] the dependence on the tube diameter was studied and it was found to be smoother. Grewal and Saxena [16] have shown that the correlation of Vreedenberg [12] predicts the heat transfer coefficient well for tube diameters of 12.7 mm but underestimates the heat transfer coefficient for larger tube diameters. Grewal [9] reviewed the influence of the pitch on the heat transfer coefficient and includes a term accounting for this influence in his previous correlation for a single tube. Zabrodsky *et al.* [10] also observed that for large particles the heat transfer coefficient decreases reducing the horizontal pitch. This is attributed to the lower particle mobility due to the restriction placed by the presence of the tubes.

The correlation of Preto [8] was disregarded in the present analysis due to the lack of theoretical support. It was developed based on a dimensionless analysis where the Nusselt and Archimedes numbers were considered. The correlation is not expected to have a large degree of applicability as the different components are not considered individually. Nevertheless the influence of the particle diameter on the heat transfer coefficient is considered, showing the presence of both, the conduction and convection mechanisms. The influence of particle size is considered through the Archimedes number.

2.2 *Radiation*

For the situations of interest to the FBC, the radiant component of heat transfer should be considered as this component becomes important for bed temperatures above 600°C. The estimative of the radiative component presents the most difficulty. Radiative heat transfer from the bed material to immersed surfaces must be conceived in two parts depending on the cooling surface being exposed or not to the passage of a bubble.

When particles contact the heat transfer surface, radiation tends to transfer some heat at the expense of the particle conduction - convective mode. This effect is larger with bigger particles because the heat transfer surface receives radiant energy from the whole of the particle's surface visible to it. Relatively less heat flows by conduction from the particle to the transfer surface through the short gas conduction path close to the point of contact [17].

The heat transfer by radiation may be characterized by an effective emissivity in which the influence of an immersed heat transfer surface on the temperature of the adjacent particles is taken into account. The radiative component can thus be obtained from:

$$h_r = \sigma\,\varepsilon_{ef}\left(T^2 + T_s^2\right)\left(T + T_s\right) \tag{2}$$

The effective emissivity decreases as the temperature difference between the bed and surface increases and when the absolute bed temperature increases. Decreasing bed temperature and supposing similar surface temperatures, the effective emissivity increases because the temperature of the bed particles remain closer to the bulk bed temperature.

The effective emissivity decreases when: i) the particle size decreases and ii) the contact time of the particles with the surface increases. This is due to the fact that the temperature of the particles is more affected by conduction heat transfer to the surface for smaller particles, and larger contact times.

The radiative heat transfer component increases with gas flow due to the increase in time fraction of bubbles contacting the surface. The bubbles open up the bed so that the heat transfer surface can see deeper into the bed where there has been less influence of the heat exchanged with the heat transfer surface on local bed temperature. For a vigorously fluidised bed, when the effective emissivity can be given from the analogy with two parallel planes:

$$\varepsilon_{ef} = \frac{1}{\dfrac{1}{\varepsilon_b} + \dfrac{1}{\varepsilon_s} - 1} \tag{3}$$

In some existing mathematical models [3, 5] a value of 0.7 for the effective emissivity is used ($\varepsilon_s = 0.8$; $\varepsilon_b = 0.85$). When the temperature of the bed particles is significantly affected, the effective emissivity should represent the reduction of the radiative flux along the time of contact. At the moment no general correlation for the effective emissivity that accounts for the discussed parameters is available. Existing measurements of the effective bed emissivity (ε_b) published in the literature [17] show that the emissivity of the bed is higher than the particle emissivity ε_p. For sand the typical values are $\varepsilon_p = 0.6$ and $\varepsilon_b = 0.85$. This effect is due to the larger area exposed by the particles, when compared to the projected area. The effective emissivity, however has to represent the effects of changes in fluidising velocities and particle diameter.

	Particle Diameter (mm)	Bed Temperature (°C)	Surface Temperature (°C)	Radiative Flux $(Wm^{-2} k^{-1})$	% Flux	ε_{ef}
Baskakov (1985)	0.32	1000	300	47	---	0.33
	0.32	900	300	39	---	0.39
	0.5	1000	300	51	---	0.36
Renzhang et al. (1987)	0.497	950	150	59	17	0.38
	0.802	950	150	78	24	0.50
Ozkaynak et al. (1980)	1.032	760	200 Assumed	80	30	0.72

Table 3 — Radiative Component of Heat Transfer and Effective Emissivities

Table 3 shows some values of measured radiative components and effective emissivities taken from the literature. Baskakov [18] and Ozkaynak et al [19] measured the radiative component of the heat transfer using a radiometer. The increase in the effective emissivity with particle diameter and with the reduction of bed temperature can be seen in the results of Baskakov. These results were obtained with Corundum Al_2O_3 particles which is a material with low emissivity ($\varepsilon_p = 0.27$; $\varepsilon_b = 0.59$). Ozkaynak et al. used sand particles of large size in a fluidised bed operated at low temperatures. Both of these facts yield a large value of the effective emissivity. Renzhang et al [20] measured the total heat transfer in a cold bed using residual slag of fired coal and in a hot FBC. The cold measurements were found to be in a good agreement with the correlation of Grewal and Saxena [16], for the conduction - convection contribution. The non - radiative component of the heat transfer for the hot bed was calculated using Grewal and Saxena correlation and the radiative component was deduced from the total heat flux.

Discrepancies on the measured value of the effective emissivity may be attributed to the experimental techniques employed. In the case of Renzhang et al. [20] the deduction of the radiative component from the total heat coefficient subtracting the conduction/convection component, tends to underestimate the radiative transfer as it is physically accepted that radiation transfers some heat at the expense of the conduction/convection mechanism, [17].

The conditions analysed in the present paper suggest for vigorously fluidised beds of large particles and temperatures typical for FBC a value of bed emissivity $\varepsilon_b = 0.85$ and an effective emissivity of $\varepsilon_{ef} = 0.7$. The radiative component (h_r) is added to the conduction/convection component (h_{cc}) calculated using the correlations presented.

3. EVALUATION OF THE CORRELATIONS

The correlations were tested for two sets of results obtained in two FBC (test no. 6 of National Coal Board - Coal Research Establishment and Test no. 26 of Babcock - Wilcox, both reported in [5], using a mathematical model [1]. The char reaction rate was calculated according to Smith [21] for bituminous coals. The details of the model with special emphasis on the heat transfer balance equations are given in [22]. The test cases selected correspond to a pilot scale (NCB - CRE) and an industrial FBC (Babcock - Wilcox), using in both cases large particles as bed material and large superficial velocity. The main operating conditions of the two test cases are summarized in table 4.

The evaluation of the correlations presented was performed by adding the radiative component. Each correlation was implemented in the model and the predicted temperature of the bed was compared to the experimental value. All the properties were calculated for the mean between bulk and tube surface temperature.

Tables 5 a) and b) show the predicted values of the heat transfer coefficients for the two cases considered. The predicted bed temperatures obtained using the different heat transfer correlations are also presented in the tables. Based on the value of the experimental bed temperature, the heat transfer coefficients which satisfies the heat balance in the model was calculated and is presented for comparison as the experimental value.

The conduction - convection component depends slightly on the predicted temperature. It may decrease increasing temperature due to the larger velocities and void fraction predicted. On the opposite the radiative component is strongly dependent on temperature, which is shown by the values obtained for h_r. The radiative components have a stabilizing effect on the model when the heat balance is applied. This explains that although large errors in the conduction - convection heat transfer coefficients occur they are smoothed due to the radiative component leading to smaller errors in the heat transfer coefficient h.

The correlation of Vreedenberg shows a reasonable behaviour in the prediction of the heat transfer coefficient although was deduced for small particles. This is due to two opposite influences: i) The conduction mechanism described in the correlation underestimates the heat transfer coefficient for large particle diameters and ii) The application of the

Geometry of Reactor	BABCOCK	NCB
Transversal section (m)	0.99 x 0.99	0.3 x 0.3
Expanded bed height (m)	0.7	0.5
Total height (m)	3.442	2.4
Wall thickness (m)	0.114	0.1
Wall conductivity ($Wm^{-1} K^{-1}$)	0.22	0.3
Operating conditions	**BABCOCK**	**NCB**
Mean diameter of feeded material (mm)	1.02	2.02
Density ($Kg\ m^{-3}$)	3000	3000-2000
Flow rate of $CaCO_3$ (Kgs^{-1})	0.0215	0.003
Air flow rate ($Kg^3\ s^{-1}$)	0.6952	0.0631
Mean temperature (K)	1075	1122
Coal feed rate ($Kg\ s^{-1}$)	0.0585	0.00642
Calculated Values	**BABCOCK**	**NCB**
Superficial velocity ($m\ s^{-1}$)	2	1.33
Bubble fraction	0.44	0.26
Global voidage	0.79	0.72
Excess air	25%	8%
Heat exchanger tubes	**BABCOCK**	**NCB**
External diameter (mm)	48.3	50
Length (m)	0.99	0.300
Number	30	10
Orientation	Horizontal	Horizontal
Display	Alternate	Alternate
Pitch (mm)	114	150
Internal fluid	water	water
Flow rate ($Kg\ s^{-1}$)	7.0	2.64
Inlet temp. (K)	373	288
Outlet temp. (K)	406	---
Coal characteristics	**BABCOCK**	**NCB**
Mean diameter (mm)	0.44	0.26
Type	Semi-bituminous	Bituminous
% mass moisture	5	6.1
% mass volatiles	40	32.0
% mass fixed carbon	50.1	46.0
% mass ash	9.9	15.9
Calorific value ($J\ Kg^{-1}$)	30.48×10^6	26.67×10^6
% mass C (d. b.)	73.2	68.2
% mass H (d. b.)	5.1	4.4
% mass O (d. b.)	7.9	9.4
% mass N (d. b.)	0.9	1.65
% mass S (d. b.)	3.0	3.8

Table 4 — Geometry and operating conditions of the simulated test cases.

correlation for very high values of gas velocity when compared with the experimental values used to obtain the correlation tends to overestimate the heat transfer coefficient. Andeen and Glicksmann introduced in the previous correlation a correction to account for the influence of velocity. Therefore the correlation of Andeen and Glicksmann underestimates the heat transfer coefficient.

Correlations	h_{cc} ($Wm^{-2}k^{-1}$)	h_n ($Wm^{-2}k^{-1}$)	$h=h_{cc}+h_r$ ($Wm^{-2}k^{-1}$)	Error h (%)	T (K)	Error T (K)
Vreedenberg (1958)	236	75	311	2	1068	- 7
Andeen and Glicksmann (1976)	92	109	201	- 35	1246	171
Glicksmann and Decker (1980)	263	67	330	21	1019	- 56
Catipovic et al. (1980)	187	84	270	- 12	1126	51
Zabrodsky et al. (1981)	135	96	231	- 25	1188	113
Grewal (1981)	240	75	315	3	1062	- 13
Experimental value	232	75	307		1075	

Table 5a) — Values of the predicted temperatures and coefficients of the heat transfer correlations. Test case of Babcock - Wilcox

Correlations	h_{cc} ($Wm^{-2}k^{-1}$)	h_n ($Wm^{-2}k^{-1}$)	$h=h_{cc}+h_r$ ($Wm^{-2}k^{-1}$)	Error h (%)	T (K)	Error T (K)
Vreedenberg (1958)	124	91	215	- 11	1171	49
Andeen and Glicksmann (1976)	63	110	174	- 28	1264	142
Glicksmann and Decker (1980)	197	77	273	13	1078	- 44
Catipovic et al. (1980)	136	87	223	- 8	1155	33
Zabrodsky et al. (1981)	118	92	209	- 14	1183	61
Grewal (1981)	163	80	243	1	1119	- 3
Experimental value	161	81	242		1122	

Table 5b) — Values of the predicted temperatures and coefficients of the heat transfer correlations b) Test case of NCB

* Values calculated to satisfy the heat balance using the experimental data.

The correlation of Grewal is a modification of the previous correlation of Andeen and Glicksmann. The constant value of 900 has been replaced by a function of the gas and particle properties. For the two test cases considered in the present study the value of that function was found to be within 10% of the constant value used by Andeen and Glicksmann. Although Grewal's correlation predicts the correct value of the heat transfer coefficient, it was deduced for small particle diameters. This correlation was expected to underpredict the heat transfer coefficient for large particles as it contains only a conduction component. The large coefficients obtained are attributed to the predicted low values of the bulk bed porosity. The value obtained for the global voidage using the expression presented in table 1 [15] led to $\varepsilon = 0.64$ for the Babcock - Wilcox case and $\varepsilon = 0.50$ for the NCB case compared respectively with the values $\varepsilon = 0.79$ and $\varepsilon = 0.72$ obtained using the mathematical model. The bed expansion ratio calculated by the mathematical model was compared favourable with experimental correlations [1]. This was mainly a result of the consideration of the bubble velocity according to [23]. Using the value of global voidage predicted by the model, the heat transfer coefficient is underestimated as in the correlation of Andeen and Glicksmann.

The correlations developed for large particle predict the heat transfer coefficient with differences of ± 25% and ± 15% for the Babcock and Wilcox and NCB cases respectively. The smaller errors obtained for the NCB case are a consequence of the larger diameters used in that case and thus the larger importance of the convective mechanism. The deviations of the correlations compared to the estimated value are in agreement with other tests [24] of the correlations. Glicksman and Decker [13] report differences up to 30% in the predicted and experimental values of the heat transfer coefficient for large bed particles.

The reasonable good agreement between the heat transfer coefficient that satisfies the energy balance in the mathematical model and the values obtained using the correlations for large particles suggest that the model correctly simulates the energy fluxes in the bed. The use of an effective emissivity of 0.7 seems to be correct for a vigorous bed as the ones simulated.

4. CONCLUDING REMARKS

In this paper, correlations for the heat transfer in a fluidised bed combustor were analysed. The influence of particle diameter and gas velocity on the individual heat transfer components were discussed. Emphasis was placed on the radiant component.

A mathematical model was used to simulated the operation of two FBC's (0.2 MW and 2 MW) with large bed particles. The heat transfer correlations were tested against the experimental results for the two cases. For the conditions tested using large particles and fluidising velocity, the correlation of Catipovic et al [14] represented the expected values more closely.

The correlations of Vreedenberg [12] and Grewal [9], although yielding correct values for the heat transfer coefficient, are subject to criticism as they only include a conduction component and they were applied here for conditions out of their regions of validity. Grewal [24] tested extensively his correlation [9] for beds of small particle diameters.

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