TECHNICAL NOTE

The influence of operating parameters on heat transferred to immersed tubes in a fluidized bed coal combustor

João F. P. Gomes
Av. Columbano Bordalo Pinheiro-85-1-H, 1000 Lisbon, Portugal

Received March 1987 and accepted for publication September 1987

Studies were conducted on a 200-mm-diameter water-cooled fluidized bed combustor to investigate the effects of particle size, bed height, temperature, and gas velocity on heat transfer from the bed to an immersed cooling tube. The experimental work was carried out by burning Portuguese anthracites from a mine in northern Portugal. The early results have demonstrated that the particle circulation between the bulk phase and the zone adjacent to the immersed surface appears to determine the mode of heat transfer.

Keywords: fluidized beds; combustion; heat transfer; coal

Introduction

Sudden and sharp increases in the price of crude oil during the decade of 1970 and the realization of decreasing reserves of both oil and natural gas have led to the reemergence of coal. Currently, a lot of R&D work has been carried out to investigate and develop gasification and liquefaction technologies to substitute oil and gas by those derived from coal gasification and liquefaction processes which require good-quality coals, and this has consequently given rise to increased efforts to employ poor-quality coals for combustion purposes. Poor coals can be defined as those with high ash and sulfur content, low carbon content, and somewhat unreactive. These types of coals cannot easily be burnt on more traditional forms of coal-burning equipment, and fluidized combustion has since emerged as a successful and practical technology for the generation of energy from poor-quality coals.

In the design of fluidized bed combustors one of the most important considerations is the knowledge of heat transfer from the bed to the immersed tubes. In bubbling-bed systems, heat transfer between a bed and an immersed heat transfer surface is considered to consist of three additive components:

(a) Convective heat transfer due to particle circulation
(b) Interphase gas convective heat transfer
(c) Radiant heat transfer

Component (a) is influenced by the volumetric flowrate of bubbles close to the heat transfer surface. The interphase gas convective heat transfer becomes important only at those interstitial gas velocities near turbulent conditions. The radiative component appears to be significant at temperatures above 700°C, but its extent is basically determined by local surface temperature. The presence of a cooler surface, for example, can modify the bed temperature adjacent to the surface, thus reducing the local radiant heat flux.

This work aims to investigate the parameters influencing heat transfer to cooling water circulating through the horizontally immersed tube placed in the bed during combustion of coal. The early results indicate that in a deep bubbling bed, the particle circulation between the dense phase and the region directly adjacent to the cooling surface appears to control the mechanism and amount of heat transferred.

Experimental setup

Figure 1 gives a schematic of the fluidized bed reactor used. The reactor is refractory steel, 20 cm in diameter, and 3 m high. It is well insulated with kaowool. The bed section height is 0.5 m, and the position of the horizontal immersed cooling tube is shown in Figure 2.

Table 1 gives the characteristics of the coal used in the experiments. Both overbed and underbed feeding of coal were used. Air is supplied through a windbox placed below a distributor plate to which standing pipes, each with six nozzles, are attached. The range of the experiment is given in Table 2. Chromel-alumel (K-type) thermocouples were used to measure temperatures at various heights of the bed. Inlet and outlet water temperatures were also recorded. One thermocouple was attached to the surface of the immersed tube.

Theory

The total amount of heat transferred to the cooling medium from the bed is

$$q = m^{\circ}(h_2 - h_1)$$

Inlet and outlet temperatures of the cooling medium can easily be obtained from these temperatures, and the respective enthalpies can be determined. The overall heat transfer coefficient can then be calculated from the equation

$$U = q/A\Delta T$$

where

$$\Delta T = (T_{w2} - T_{w1}) \ln\left(\frac{T_b - T_{w1}}{T_b - T_{w2}}\right)$$

The overall heat transfer between a bed and an immersed surface is considered to be the sum of the following components

(1) Convective heat transfer due to particle circulation between the dense phase and the zone very adjacent to the immersed zone
(2) Interphase gas convective heat transfer
(3) Radiative heat transfer

Previous studies[1-4] have indicated that the convective heat transfer due to the particle movement is particularly dominant with bubbling-bed systems and for a particle size range of 40 μm to about 1 mm. It is the particles which have high volumetric heat capacity to deliver heat from the bulk phase of the bed to the immersed heat transfer surface. Once they are in the region adjacent to the immersed surface, particles exchange heat with the upgoing gas, and heat has to transfer by conduction through the gas phase, which ultimately forms the main resistance to heat transfer due to the low thermal conductivity of gas.

The reason for an increased heat transfer rate due to higher temperature can be explained as the consequence of the increase in gas thermal conductivity with temperature. There is a limit for the particle size reduction to enhance heat transfer coefficient because below the limit size interparticle forces restrict particle movement. This decreases the heat transfer coefficient.

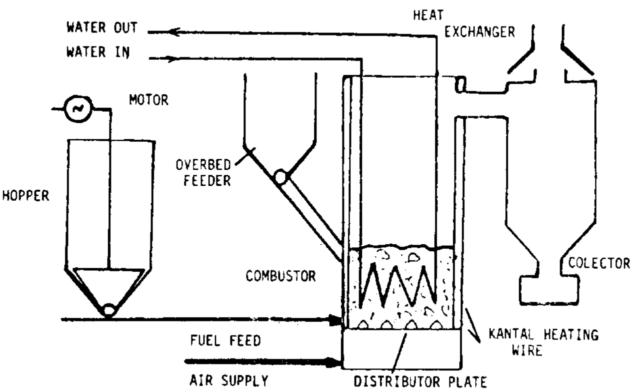

Figure 1 The experimental set-up

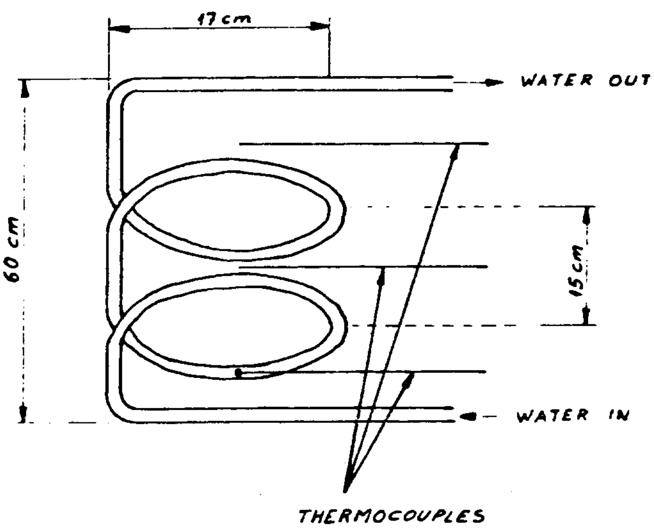

Figure 2 The immersed cooling coil

The interphase gas convective component enhanced particle-to-surface heat transfer due to augmented gas phase convective heat transfer. It is more significant at particle sizes higher than 0.8 mm and as static operating pressure increases. There are several empirically developed correlations[2,3] which assume that the gas convective component is relatively insensitive to increases in gas velocity. The correlation developed by Denloye and Botterill[5] takes the form

$$U_{gc}d_p^{1/2}/K_g = 0.86\mathrm{Ar}^{0.39}$$

for $10^3 < \mathrm{Ar} < 2 \times 10^6$.

The radiative component of the transferred heat is difficult to estimate. It becomes important at temperatures above 700°C, and it appears that the radiant mode gives rise to a transfer of heat at the expense of the component due to particle circulation. Consequently, these two components are not strictly additive.

Zabrosky[3] suggested an approximate correlation for the maximum bed-to-surface heat transfer coefficient correlation as follows:

$$U = 35.8d_p^{-0.36}K_g^{0.6}C_p^{0.2}$$

This relation predicts reasonably well the effect of temperature on gas thermal conductivity until the radiative component becomes significant.

Results and discussion

Figure 3 compares experimentally determined values of the heat transfer coefficient with those predicted from the Zabrosky correlation for various temperatures. At temperatures below 700°C the agreement appears to be satisfactory, but above 700°C the experimentally determined values tend to be greater,

Table 1 Characteristics of the coal used

Proximate analysis	%
Ash (as analyzed)	44
Volatile matter (as analyzed)	5
Moisture (as analyzed)	15
Fixed carbon (as analyzed)	34
Calorific value	14,500 MJ/kg

Table 2 The range of the experimental work

Bed operating temperature range (T_b)	800–950°C
Bed height range	0.2–0.5 m
Gas velocity	0.32–1.2 m/s
Particle size range (d_p)	0.55–2.5 mm (with no fines)
Water inlet temperature (T_{w1})	22°C
Water outlet temperature (T_{w2})	89°C

Notation

A	Heat transfer surface area, m^2
Ar	Archimedes number
C_p	Density, kg/m^3
d_p	Particle size, m
h	Enthalpy, kJ/kg
K_g	Gas thermal conductivity, W/m·K
m°	Mass flowrate, kg/s
q	Heat flux, W
T_b	Bed temperature, K
T_{w1}	Water inlet temperature, K
T_{w2}	Water outlet temperature, K
ΔT	Temperature difference, K
U	Heat transfer coefficient, W/m^2·K
U_{gc}	Convective heat transfer coefficient for gases, W/m^2·K

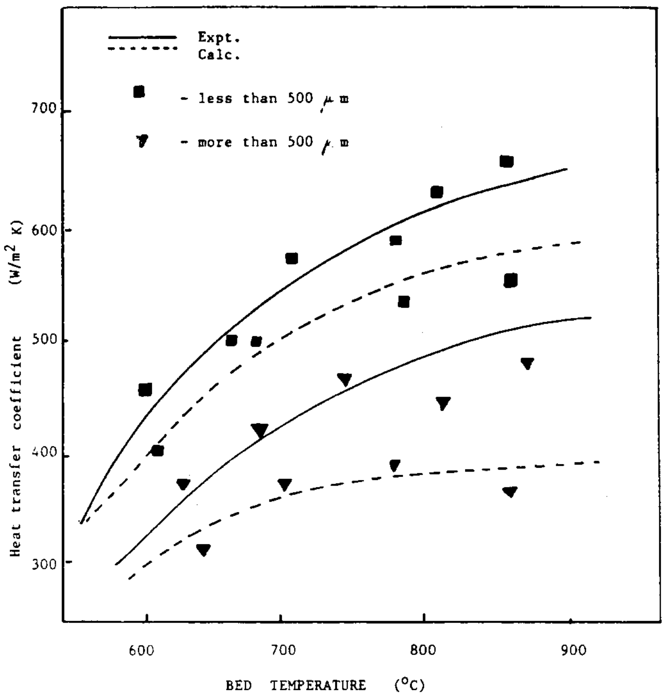

Figure 3 The comparison of experimental data with Zabrosky correlation

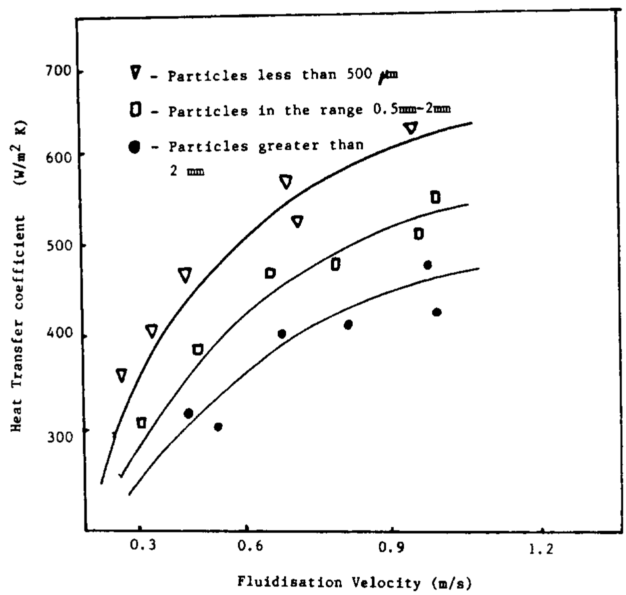

Figure 4 The variation in heat transfer coefficient with fluidization velocity for various particle size used

which could confirm the theory of radiative heat transfer being responsible for the mechanism of heat transfer. As shown in Figure 3, with a system using larger particles the discrepancy between the experimentally observed values and Zabrosky correlation is even greater. This can be due to the heat transfer surface receiving and radiating energy from and to the whole of the particle's surface visible to it. Consequently, relatively less heat can be exchanged by conduction through the gas phase.

As the ash was accumulated in the bed, there was a variation in the bed emissivity. This could be due to the refractory character of ash, and such materials usually have lower emissivities. This aspect has to be studied in greater detail.

The experimental results demonstrated that the bed height does not have a significant influence on the heat transfer coefficient for the range of the gas velocities used, though with the smaller particles the heat transfer coefficient tended to increase with bed height. This could be due to the greater expansion of the bed at the onset of fluidization with smaller particles.

The observation in the variation of the heat transfer coefficient with gas velocity confirms results of earlier works[1]. The value of the coefficient increases as gas velocity increases. However, in the system employed it was not possible to reach the maximum value before the expected fall with further increase in gas velocity, because of ash accumulation in the bed, which tended to increase the bed height and produce defluidization. Consequently, in order to maintain the bed height at a present value and to achieve good fluidization, the gas velocities were kept at those values in the increasing region of the heat transfer coefficient.

Figure 4 summarizes the experimental findings. Experimental work demonstrated that the heat transfer coefficient was enhanced with the increase in bed temperature, as shown in Figure 5. This is expected because all the components that contribute to the overall heat transfer are augmented by the increase in temperature.

The radiative component most certainly becomes significant above 700°C. The gas thermal conductivity increases with increasing temperature; therefore, conduction through the gas layer takes place at a greater rate.

The effect of particle diameter on the heat transfer is more complex. At lower particle sizes (i.e., below 600 μm) the heat transfer coefficient appeared to decrease with an increase in particle size. This was believed to be due to restriction of particle movement as a result of interparticle forces somewhat limiting the particle circulation. However, with particles approximately 500 μm to about 6 mm the heat transfer coefficient appeared to be relatively independent of particle size, as illustrated in Figure 6. The results also indicate that the comparative independence on particle size moves to rather higher mean particle sizes as the bed temperature increases.

The reported results have demonstrated the influence of various parameters on heat transfer occurring during a

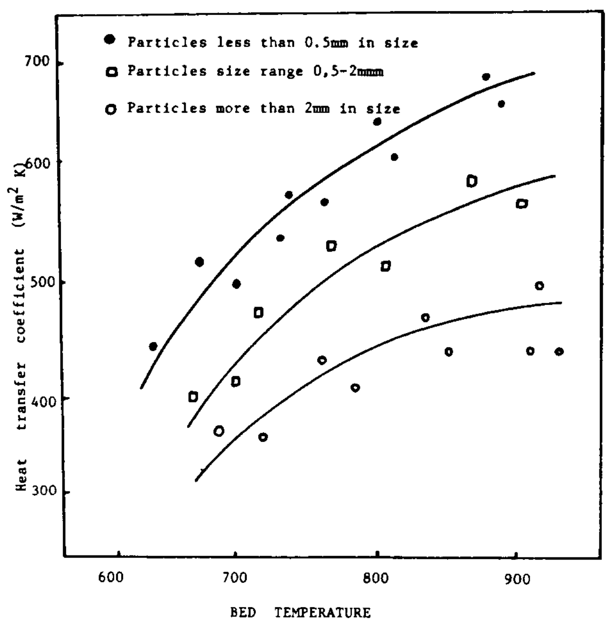

Figure 5 The effect of bed temperature on heat transfer coefficient

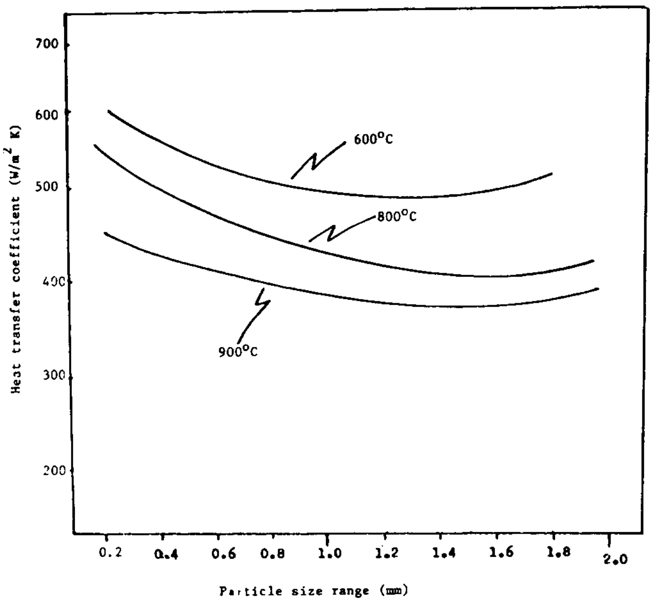

Figure 6 The effect of particle size range on heat transfer coefficient for various bed temperatures

combustion study in a fluidized bed. Further studies need to be carried out, but there results allow us to obtain important conclusions for the design of fluidized bed boilers.

Acknowledgment

The publication of this work was partially covered by Junta Nacional de Investigação Científica e Tecnológica, Lisboa, Portugal.

References

1 Mickley, H. S. and Fairbanks, D. F. Heat transfer to fluidized beds. *AIChE J.* 1955, **1**, 374
2 Denloye, A. O. O. and Botterill, J. S. M. A theoretical model of heat transfer to a packed or quiescent fluidized bed. *Chem. Eng. Sci.* 1978, **33**, 509–515
3 Zabrosky, S. S., Antonishin, N. V., and Parnas, A. L. On fluidized bed-to-surface heat transfer. *Can. J. Chem. Eng.* 1976, **54**, 52
4 Zabrosky, S. S. Compound heat exchange between a high temperature gas-fluidized bed and a solid surface. *Int. J. Heat Mass Transfer* 1973, **16**, 241
5 Denloye, A. O. O. and Botterill, J. S. M. Gas convective heat transfer to packed and fluidized beds. AIChE Symp. Series, 1978, pp. 176, 194