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Technical Note

Augmentation of heat transfer by deflectors on circulating fluidized bed membrane walls

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Abstract

It is shown experimentally that the addition of angled deflectors to the fin region of membrane water-wall heat exchanger surfaces in circulating fluidized beds can lead to a significant increase in local and overall suspension-to-wall heat transfer. The experiments were carried out in the 12 MWth circulating fluidized bed (CFB) boiler at Chalmers University. The results are consistent with calculations based on renewal of packets traveling along the fin. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Fluidization; Heat transfer; Membrane water-walls; Deflectors

1. Introduction

During the past two decades, circulating fluidized bed (CFB) boilers have become widespread for power generation and raising steam by combustion of coal, biomass, petroleum coke, etc. A major portion of the heat is extracted from the main combustion chamber (called a riser) by membrane water-walls employed, as in conventional boilers, as the walls of the combustion chamber. The tubes and connecting fins are almost vertical. Favorable heat transfer coefficients are achieved because of particle exchange between the bulk suspension in the riser and the heat transfer surface. For reviews of CFB heat transfer see [1–5].

An important finding in CFB studies is that heat transfer coefficients decrease as the vertical length of the exchange surface increases, while local heat transfer coefficients decrease with increasing distance below the top of the exchange surface, e.g. [4,6–8]. This occurs because CFB boilers operate in the fast fluidization flow regime where a relatively dilute gas–solid suspension is conveyed upwards in the core of the riser at velocities of typically 5–10 m/s, while relatively dense clusters and streamers of particles descend along the outer wall at typical velocities of 1–2 m/s. As these streamers descend along the wall, their particles cool due to both convection and radiation. As they cool, the driving force for further transfer decreases, causing a drop in heat transfer coefficient. This process is frequently modeled by extending the "packet model" introduced for bubbling beds by Mickley and Fairbanks [9], where transient heat transfer occurs to fresh packets of particles arriving from the bulk and traveling along the wall, acting as semi-finite media.

Given this prevailing mechanism of heat transfer, the extent of transfer could be augmented if the frequency of renewal of fresh packets at the wall could be increased. Wu [10] found that a trip wire at the leading edge of small heat transfer probe flush with the wall strongly affected the local transfer rate by deflecting the particle layer from the wall and allowing a fresh particle layer to form. Similarly Lints and Glicksman [11] note that protrusions only one particle diameter in height disrupt cluster flow patterns. Zheng et al. [12], Bai et al. [13], and Bu and Zhu [14] showed that horizontal rings on the

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Nomenclature

h	heat transfer coefficient, W/m^2 K
m_i	mass flow of particles from core to wall region
L_{st}	distance traveled by streamer before disintegrating, m
T_b	bulk suspension temperature of dilute core in riser, °C
U	superficial gas velocity, m/s
Z	vertical coordinate measured from primary air distributor, m

outer wall of CFB risers are able to scrape particles off the wall as they descend along it.

The vertical distance of travel of streamers is of the order of 1 m for flat surfaces [8,11]. However, for membrane water-walls, streamers travel down considerably further along the fins between the tubes than along the exposed curved tube surfaces [2,10,15,16]. As a result, packets on the fins travel further before being renewed than packets in contact with the tubes. Clearly heat transfer could be enhanced if the renewal frequency could be increased. Here we consider a means of enhancing heat transfer by installing deflectors along the fins. Since the overall size of many large CFB boilers is primarily governed by the need to provide sufficient transfer surfaces to extract the heat released by combustion, any practical means of raising the overall suspension-to-wall heat transfer coefficient could result in significant capital savings.

2. Experimental equipment

The experiments were conducted in the 12 MWth CFB boiler at Chalmers University of Technology in Göteborg, Sweden. The unit is large enough (1.4 × 1.7 m^2 cross-section, 13.5 m tall) that it provides highly credible information for industrial scale CFBC units [17].

The fuel is introduced through the inclined fuel chute on the front of the boiler. The exit duct and return entry port for external particle recirculation are both on the rear (1.7 m wide) surface, while secondary air ports are located on the front and rear walls, 2.2 m above the primary air distributor plate, inclined towards the bottom at an angle of 15°. The outlet has its upper edge 1.6 m, and its bottom edge 4 m, below the furnace roof. The front and rear walls of the furnace are covered with refractory, while the side walls are membrane surfaces composed of 60.3 mm o.d. cooling tubes connected by fins of width 8.8 mm extending from the top of the side walls to 2 m above the distributor plate. The crests of the tubes protrude 27 mm beyond the exposed fin surface. 50.8 mm diameter measurement holes are provided along the vertical center-line 2.5, 4.0, 4.5, 5.0, 5.5, 6.0, 8.0, and 11.0 m above the distributor plate. Two additional holes are located 485 mm to the left and right side of the center-line of the membrane wall at three of these heights, $z = 4.0$, 5.5, and 11.0 m. For comparison, two holes are also located 8 and 11 m above the distributor, on the center-line of the front refractory-lined wall. The measurement holes are cut through the fins and the two tubes without otherwise affecting them. Suspension temperatures are measured by thermocouples at three positions in the bottom of the combustion chamber and three at the top. The boiler is equipped with pressure transducers along one side wall to determine the vertical pressure distribution and the vertical distribution of the cross-sectional average suspension density. A data acquisition system recorded the time-averaged boiler operating conditions such as fluidization velocity, pressure drop, temperature, etc.

Measurements of heat transfer and local temperature were obtained through the measurement ports on the side and front faces. Each port was centered on the axis of a fin, with wings as shown in Fig. 1, continuing the tube surface so that the furnace-side hydrodynamics were undisturbed by the ports. A heat flux meter, described in detail by Andersson et al. [18], was installed to determine the heat flux at the measurement position. The probe received heat on the hot end of the conduction rod, flush with the fin, whereas the other end of the

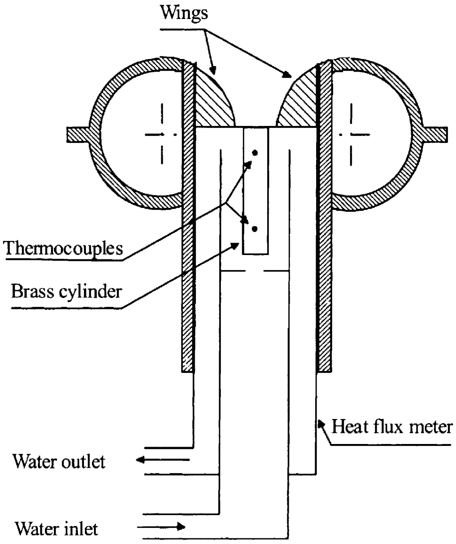

Fig. 1. Cross-section of heat flux meter in measurement position.

rod was cooled by water. Thermocouples are employed to find the temperature gradient. The temperature gradient of the rod, together with the calibration constant of the meter, gives the heat flux to the surface of the rod. To estimate the heat transfer over the entire section, corrections are needed to account for both: (a) the fact that heat flux to the fin is less than that to the tube surfaces; (b) differences in the temperature and emissivity of the wall and the heat receiving surface of the meter heat flux. The procedure for estimating overall membrane heat transfer coefficients based on the heat flux meter results was discussed by Golriz [15,19]. After correction, the maximum uncertainty in the heat transfer coefficient, taking into consideration uncertainties in wall temperature, wall emissivity, and bulk suspension temperature was less than 8%.

Temperatures in the furnace, including the bulk temperature used in determining the heat transfer coefficients, were measured by a double-shielded multi-thermocouple probe inserted into the combustion chamber through one measurement port at a time. The probe has a series of 1 mm diameter Chromel–Alumel thermocouples with a thermal time constant in air of 1.65 s. The error due to conduction along the thermocouple is negligible since the leads are partly placed in the flow direction and the thermocouple is very long compared to the thermocouple diameter. Local temperatures were measured simultaneously by thermocouples located 0.5, 6, 12, 18, 30, 45, 60, 90, 200, and 300 mm from the fin surface. The two concentric radiation shields protect the thermocouple from radiative exchange with the cold wall, and from being damaged by large particles. A correction procedure is necessary close to the wall. The accuracy of the method depends on several parameters, such as fluid temperature, emissivity of the thermocouple and the convective heat transfer coefficient to the thermocouple [8,20]. The uncertainty in temperature readings is estimated to be less than 4% [20].

Visual observations were also carried out through windows of 50.8 mm diameter installed in the measurement ports. These provided a limited view of clusters descending along the fins. The suspended particles were primarily composed of silica sand of mean diameter 270 μm and density 2600 kg/m^3. The fuel was a bituminous coal with a 0–20 mm feed size.

3. Experimental results

Observation through the 50 mm diameter, windows [15,21] confirmed the presence of streamers falling along the central fin for the operating conditions investigated (superficial gas velocity 5.7 m/s, bulk bed temperature 850 °C, primary/secondary air ratio 3:1, total riser pressure drop 6.4 kPa). Hot clusters of particles could be seen arriving from the bulk and beginning to descend along the fin, while other particles slid around the tube surface and gathered in the fin region, where they again formed streamers. A wall streamer 8 m above the distributor plate is illustrated in Fig. 2. A cross-section of part of the membrane wall is shown above the picture. The black areas show relatively cool particles descending along the fin region. Streamers were observed to be thicker and to persist at the wall longer in the lower part of the combustor than near the top.

Experiments were next carried out with a sloping deflector baffle installed via different ports above the measurement port to determine its influence on the temperature distribution and heat flux. Since the ports were 0.5 m apart in the lower part of the combustion chamber but 1 m apart 10.0 m above the distributor plate, it was only possible to test multiples of 0.5 m. Fig. 3 shows temperature profiles determined using the multi-thermocouple probe described above at heights of 4.0 and 10.0 m above the distributor, with the deflector absent or located above the measurement position. The data show that the bulk suspension temperature is unaffected at both heights by the presence of the deflector. However, close to the fin there is a significant influence of an upstream deflector, with the deviation from the non-deflector (smooth fin) case being greatest, as one would expect, when the deflector is closest to the measurement level. The recorded temperature near the fin increases with the deflector in place, indicating greater renewal of particles from the bulk. The deflector is seen to affect the temperature profile over a distance of at least 1.5 m for the lower measurement position and 1.0 m for the upper one.

Fig. 4 shows recorded suspension-to-fin heat transfer coefficients for time intervals of nearly 200 s, with the

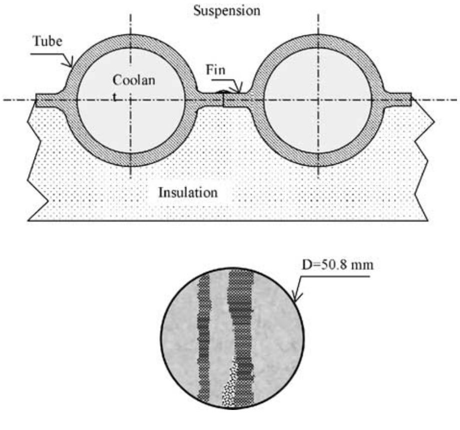

Fig. 2. Plan view of membrane wall geometry and of particles descending along a fin of the membrane wall in the 12 MWth CFB boiler at normal conditions.

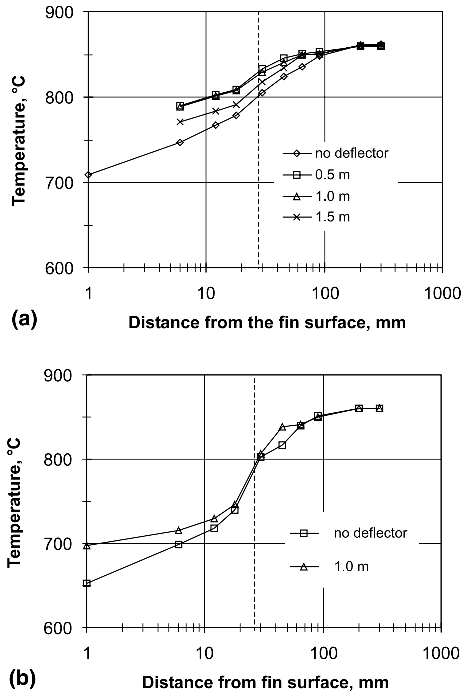

Fig. 3. Effect of upstream deflector on lateral temperature distribution near fin: $U = 6.5$ m/s, $T_b = 860$ °C, primary/secondary air ratio = 2:1; total pressure drop across riser = 5.3 kPa. Deflector when installed was 0.5, 1.0 and 1.5 m above measurement level: (a) $z = 4.0$ m; (b) $z = 10.0$. Dashed line indicates the tube crest projection.

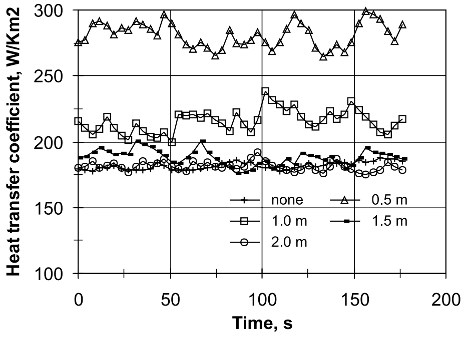

Fig. 4. Influence of deflector 1.0 m upstream on instantaneous heat transfer coefficient to fin for $z = 4.0$ m. $U = 5.5$ m/s, $T_b = 850$ °C, primary/secondary air ratio = ∞, total pressure drop across riser = 6.0 kPa.

heat flux meter located 4.0 m above the primary air distributor and either no deflector or a single deflector 0.5, 1.0, 1.5, and 2.0 m above the measurement level. There are significant fluctuations of the heat transfer coefficient, especially when the deflector is not far upstream, with a period of 10–15 s. These fluctuations are likely due to the build-up of new clusters/streamers downstream of the deflector after a large streamer was deflected into the bulk stream. This interpretation is consistent with visual observations of the dynamic pattern through the viewing ports in the wall region of the boiler. Due to the thermal inertia of the meter, it can be assumed that the maximum/minimum values of the heat transfer coefficient are higher/lower than that indicated by the meter. However, the average local transfer coefficients should not be affected by the thermal inertia of the meter, because the variation in the boundary layer in a CFB boiler is almost periodic in nature. It is seen that the deflector had a profound influence on the time-averaged heat transfer coefficient when close to the fin. The coefficient was 55% higher than for the smooth fin case when the deflector was 0.5 m above the flux meter. There was also an appreciable augmentation in the heat transfer coefficient for deflector-to-measurement-level separations of 1.0 and 1.5, indicating that the survival length of streamers can be at least 1.5 m for the conditions studied. However, there was little or no influence on the measured heat transfer coefficient with the deflector 2.0 m upstream. With the heat flux meter 10.0 m above the primary air distributor, there was negligible change in heat transfer coefficient when the deflector was located 1.0 m above it. This no doubt arose because of the dilute conditions at the top of the combustor, with radiative heat transfer dominant, and the heat flux meter not sensitive enough to detect small changes in heat transfer coefficient.

4. Discussion

The packet or penetration theory (e.g. [22,23]) suggests that the time-averaged convective heat transfer coefficient is approximately proportional to $L_{st}^{-0.5}$, where L_{st} is the mean vertical distance traveled by streamers before being renewed by fresh particles from the bulk (core) of the riser. Indeed the results in Fig. 4 are consistent with this trend if radiation is assumed to provide approximately 70 W/m^2 K. Renewal due to deflectors can clearly reduce L_{st}, thereby augmenting the convective component. Some enhancement of radiative transfer should also occur because the particles "seen" by the wall will, on average, be hotter. Fig. 5 shows a schematic representation of the influence of a series of deflectors, each causing downflowing streamers at the wall of the vessel to be replaced by fresh (hot) ones. Clearly, such deflectors can augment heat transfer to membrane walls.

While this study confirms that deflectors can enhance heat transfer in CFB combustors, many questions remain before they could be used in commercial units:

- What is the optimum deflector shape, size and spacing?

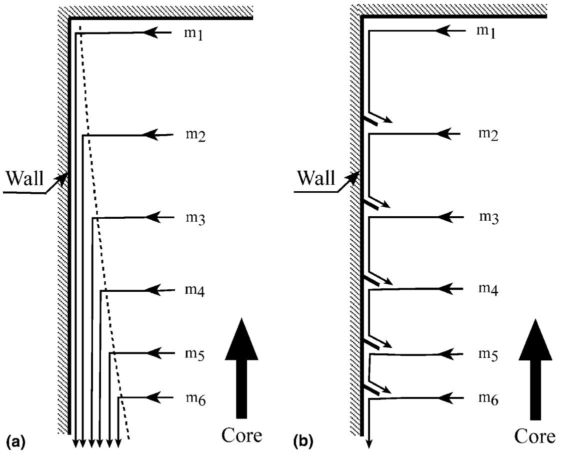

Fig. 5. Schematics showing solids motion along combustor wall: (a) without deflectors; (b) with a series of downward-sloping deflectors affixed to the wall.

- Should the deflector only cover the fins, or the tubes also?
- What is their effect on the overall pressure drop?
- What is their effect on axial dispersion of gas and particles? (Some preliminary works [14] indicate that this effect is probably small for realistic deflector sizes.)
- Can the deflectors survive the wear associated with the falling streamers?
- Can membrane walls equipped with such deflectors be manufactured economically?

Given the substantial improvement in heat transfer coefficient which are possible, it is important that further work be conducted to answer these questions.

5. Conclusions

Installation of an angled protruding deflector on a fin of a membrane water-wall affects the downstream lateral temperature profile and, consistent with the packet/renewal theory, improves the suspension-to-fin heat transfer. Adoption of such deflectors could decrease the heat transfer area and volume of large-scale CFB combustors.

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