Investigations on Heat Transfer Between a Bubbling Fluidized Bed and Immersed Tubes for Heat Recovery and Power Generation

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1. Abstract
The present research deals with the heat transfer between a bubbling fluidized bed and a single tube exchanger. Theoretical estimates of the heat transfer coefficient have been obtained by adopting a computation procedure from the literature. Experimental data have been produced with a dedicated test facility. The results confirm the high heat transfer coefficient that establishes in a bubbling fluidized bed (up to 200 Wm⁻²K⁻¹) and, thus, the suitability for a simple coupling between a fluidized bed and external devices for power generation.

Keywords: fluidized bed, heat transfer, heat exchangers

2. Introduction
Among other advantages of the fluidized bed (FB) technology for combustion, the large heat exchange coefficients in the bed and the capacity to keep clean the submerged surface are relevant when the heat extraction from the bed is the main requirement of the process [1]. This is the case of the co-generation of heat and power at small scale from FB combustion of solid fuels, also including wastes or residual materials. Liquid, vapor or gas streams can be easily heated up to high temperature by adopting tube exchangers located in the bed region, even operating at high pressure provided that the tube size is small enough. An array of tubes can also be employed since the abrasion exerted by the bed material contributes to keep clean the external surface of the tubes and to remove residues locked in the interstices of the tube array.

The utilization of a high temperature, high pressure fluid stream in an external standard machine allows for heat and power generation, but proper and effective coupling of the two devices firstly needs the evaluation or the experimental determination of the transfer coefficient for the heat exchanger.

The present research deals with the heat transfer between a bubbling fluidized bed and a single tube exchanger. Theoretical estimates and experimental data are reported and commented.

3. Experimental
The experimental apparatus for measurements of heat transfer with an immersed tube is depicted in Fig. 1. A 120 mm ID, 500 mm high fluidized bed has been used. The fluidization column is heated by means of an external electrical furnace. The immersed tube was made in AISI 304 is 4 mm ID, 6 mm OD. The tube is suspended from the open top of the, thus it is
purposely bended as shown in Fig. 1. Since the two vertical legs are thermally insulated, the length of the immersed tube is 300 mm.

A bed of silica sand 0.2-0.4 mm size is used under bubbling fluidization regime with a total expanded height of about 200 mm.

The gas stream entering the tube exchanger is provided by a bottle, so the pressure can be easily changed. A flow meter is used for measuring the gas flow rate after a cooling stage and a valve for flow regulation. Two thermocouples measure the stream temperature immediately before (T1) and after (T2) the immersed exchanger. The bed temperature (T_{bed}) is measured with a further thermocouple as well.

![Experimental apparatus for FB heat transfer measurement.](image)

### 4. Theoretical computation of the heat transfer coefficient

Following the chapter 11 of Kunii and Levenspiel [2], the general equation for computing the heat transfer coefficient $h$ in a bubbling fluidized bed is given reads:

$$
\begin{align*}
    h &= \alpha_w \left( h_r + h_g \right) + \\
    &\quad \frac{1 - \vartheta_w}{1 + \frac{K_{\text{fl}}^g c_p g^2 \rho g u}{1}} + 1
\end{align*}
$$

(1)

The explanation of symbols and parameters of Eq. 1 can be easily found in the cited source [2]. The whole procedure of heat transfer calculation has been implemented in MS-Excel worksheet. Figure 2 shows the results of $h$ computation as a function of the fluidization velocity $u_0$ (A) and the bed particle size $d_p$. (B), at fixed bed temperature T_{s}=1073K. The curves are parametric in the tube wall temperature T_{W}. The bed particle size exerts a larger influence on the heat transfer coefficient with respect to the fluidization velocity. Thus, small particles are recommended for improving the heat transfer [2].
5. Experimental results

Figure 3 reports the results of experimental measurements in terms of temperature difference $\Delta T = T_{\text{bed}} - T_2$ between the bed and the gas at the tube exit. The tests have been carried out using helium at 4 bar in the tube and air as fluidizing gas ($u_0 = 0.31$ m/s; $u_0/u_{mf} = ???$ m/s). The bed temperature was around 550°C.

The overall heat transfer coefficient $H$ has also been evaluated with reference to the external tube surface and the average gas temperature $(T_2 + T_1)/2$. The calculated values of $H$ are reported in Fig. 3 (right Y-axis).

It appears that the exit temperature $T_2$ is very close to $T_{\text{bed}}$. The increase of $\Delta T$ with the helium flow rate is the consequence of the augmented power requested for heating up the gas stream. The overall heat transfer coefficient $H$ increases with the mass flow rate, as a consequence of the increased gas velocity and, hence, the improved internal heat transfer coefficient. $H$ attains a maximum value of 200 W/m$^2$K$^{-1}$ in the test conditions. This value is well in agreement with the previously reported theoretical estimates and significantly higher than values obtained in turbulent furnaces or tubular exchangers, i.e. 20-50 W/m$^2$K$^{-1}$ [3]. It is also remarkable that the maximum thermal power transferred by the immersed, 60mm OD, 300mm long tube is around 230 W.
Fig. 3  Temperature difference and overall heat transfer coefficient for helium as a function of the gas flow rate.

6. Conclusions
High coefficients of heat transfer have been calculated for a typical FB application. Small sizes of the bed material are recommended for improving the heat transfer in fluidized bed heat exchangers.
The experimental tests demonstrate that the overall heat transfer attains a maximum value as high as 200 Wm$^{-2}$K$^{-1}$, in agreement with theoretical estimates.
Future activities will be devoted to the systematic investigation of the influence of various process variables and parameters (e.g., gas nature, gas pressure, bed particle size).

7. References