

Heat Transfer between a Horizontal Tube Bundle and Fine Particles with Air or Steam

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INTRODUCTION

This paper reports experimental data on heat-transfer between a single tube in a tube bundle and cracking catalyst or fine sand, fluidized with air or with superheated steam. The interest in the application of superheated steam arises from studies into the drying of brown coal and other minerals, on the large scale, by application of superheated steam drying (Potter and Keogh, 1979; Potter, 1980; Potter and Keogh, 1981; Beeby et al., 1981; Potter et al., 1982).

Of interest in the studies are such questions as the dependence of heat transfer coefficient on temperature and in the case of porous adsorbent solids with superheated steam the dependence, if any, on adsorption-desorption processes. The achievable heat transfer coefficients are also of importance from the viewpoint of design and optimization. To come to grips with these matters, in a manner free from the complexities of working with coal, preliminary studies have been conducted with cracking catalyst and fine sand and ballottini.

LITERATURE REVIEW

Heat transfer in fluidized beds is strongly dependent on the local bubbling regime which can as yet not be precisely predicted. The slugging fluidized bed is most completely defined and a model is available (Xavier and Davidson, 1978) which has been tentatively extended to tube bundles. Horizontal tube bundles may constitute the next most precisely defined situation since the tubes lead to a more uniform distribution of bubbles, and a marked reduction in bubble size (Nguyen et al., 1979). The tube bundle may also slow down markedly the solids movement, as has been demonstrated, as yet only for a small model system, by Chen et al. (1983). Chen et al. demonstrated a reduction in average axial solids velocity from about $0.2 \text{ m}\cdot\text{s}^{-1}$ in an internals-free bed, down to near zero in a densely-packed bundle. As expected such restriction of solids movement adversely affects the heat transfer coefficient at surfaces in the bed. Gelperin et al. (1969) provide data which suggest that the configuration employed in the experiments, viz., 25.4 mm O.D. tubes on a 50.8 mm triangular pitch, would reduce the maximum coefficient of heat transfer to about 75% of the single-tube value. The results of McLaren and Williams (1969) suggest a similar reduction.

Extensive experimental effort and theoretical investigation have resulted in many correlations being proposed for the heat transfer coefficient for horizontal tubes in fluidized beds of particles. Articles by Grewal (1981) and Grewal and Saxena (1980, 1981a, 1983) present a comprehensive list for estimation of heat transfer coef-

ficients and maximum heat transfer coefficients for both single horizontal tubes and bundles of horizontal tubes. The more commonly used correlations for the maximum coefficient range from the simple semiempirical Zabrodsky equation (1966):

$$h_{\text{MAX}} = 35.8 k_g^{0.6} d_p^{-0.36} \rho_p^{0.2} \quad (1)$$

through those of Grewal and Saxena (1983)

$$Nu_{\text{wpm}} = 0.9 (ArD_{12.7}/D_T)^{0.21} (Cp_s/Cp_g)^{0.2} \times (1 - 0.21(P/D_T)^{-1.75}) \quad (2)$$

to the complex theoretical model of Xavier and Davidson (1981).

The predicted values of maximum heat transfer coefficients from these correlations tend to be similar especially when used for air and sand at normal temperatures, Table 1.

The agreement is not as good when unusual conditions or gases are encountered, for instance with an increase in temperature or a change of gas as shown. The properties of the particles are also likely to introduce differences in the predictions.

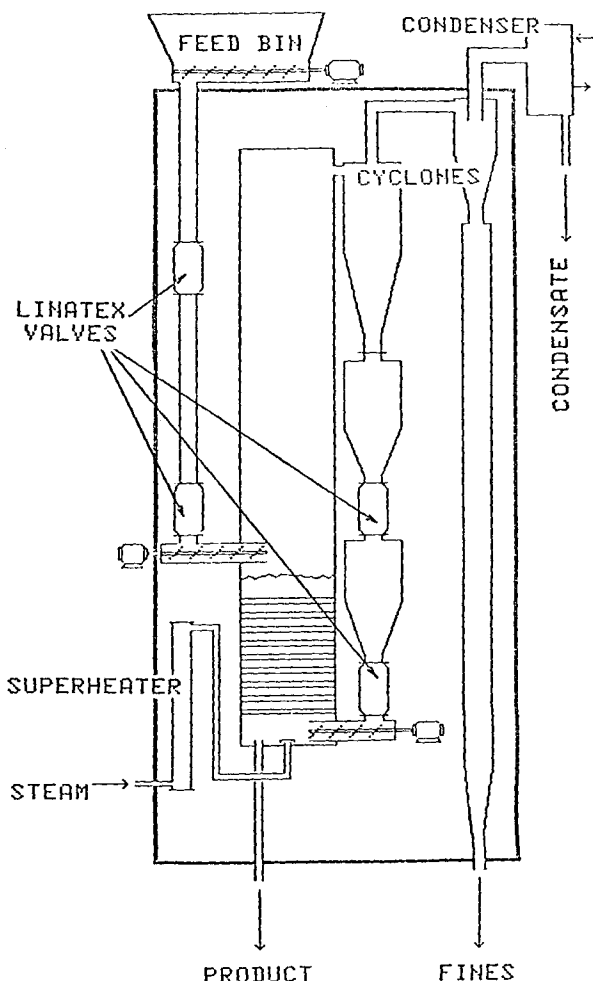


Figure 1. Pilot-plant dryer used for heat transfer measurements. When steam is not employed but air, the condenser is replaced by a bag filter.

TABLE 1. PREDICTED MAXIMUM HEAT TRANSFER COEFFICIENTS (W/m²·K)*

	Zabrodsky (1966) Eq. 1	Grewal & Saxena (1983) Eq. 2	Xavier & Davidson (1981)
Air 50°C	596	516	558
Air 200°C	723	585	693
Steam 200°C	600	484	627

* Material considered is 82 μm sand; all gases at 1 atm. pressure; and tube configuration taken as 0.025 m diameter horizontal tubes on 0.051 m triangular pitch.

Material	Surface Mean Diameter (μm)	Size at 10% Less Than (μm)	Size at 90% Less Than (μm)	Particle Density (kg/m^3)
Sand 1	82	64	124	2,600
Sand 2	77	60	122	2,600
Ballotini	134	95	250	2,500
FCC	57	41	92	900

* Measured and literature values.

Mickley and Fairbanks (1955) in heating a bed of microspheres fluidized with ammonia found heat transfer coefficients about 50% higher with ammonia than with air, whereas using a bed of glass beads the coefficients for air and ammonia were very similar. They explain the observation in terms of an additional heat capacity of the solids because of adsorbed ammonia. Baskakov et al. (1973) sprayed water onto porous charcoal particles and found that spraying led to an increase in heat transfer coefficient from 190 to 240 $\text{W}/\text{m}^2\cdot^\circ\text{C}$, the particles absorbing 13% w/w moisture. They argued that the increase in heat transfer coefficient was brought about through increase in the particle heat capacity alone. Schlünder (1981) notes that, in many practical applications, vaporization of a liquid may also be involved, if not predominant, and suggests that in formulating models of the heat transfer process, the heat capacity of the solid may be replaced "by the total enthalpy change of the particulate material."

Where there is the possibility of desorption at the hot surface followed by readsorption in the (relatively) cold bulk, there is the possibility of an additional mechanism of heat transfer to the bulk bed. When a material such as brown coal is considered, allowance has to be made for the required moisture level, e.g., a typical as-mined brown coal contains 2 kg water per kg dry coal and exerts the vapor pressure of water until the moisture is reduced to about 0.8 kg water per kg dry coal, thereafter drying is from capillaries, the partial pressure of water vapor gradually decreasing as the moisture level is reduced. At very low moisture levels, desorption becomes a factor. The behavior is hysteretic as the dry coal is ex-

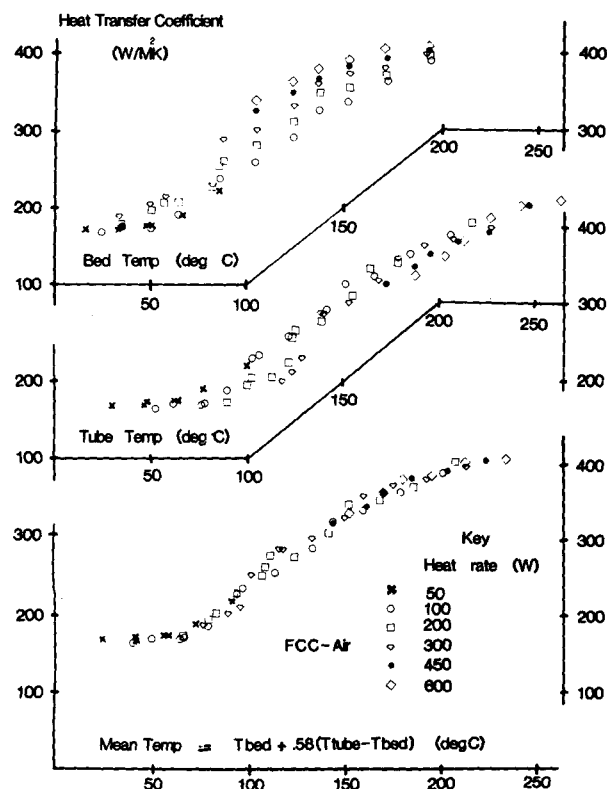


Figure 2. Maximum heat transfer coefficient measured for FCC-air plotted vs. (a) bed temperature (b) tube temperature and (c) mean temperature.

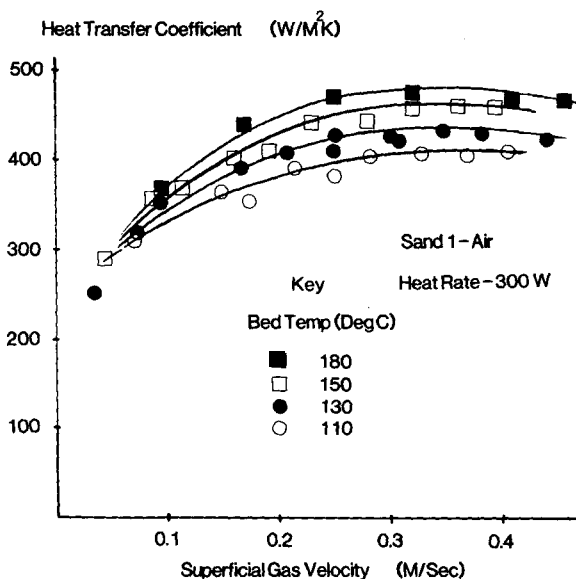


Figure 3. Heat transfer coefficient vs. superficial gas velocity for Sand 1-air, at constant heat-flux and varying bed temperatures.

posed to the water vapor and picks up moisture initially by adsorption and then by capillary condensation. Typically the coal picks up only about 0.2 kg water/kg dry coal when the partial pressure of water vapor is restored to 1 bar. The drying situation will be reviewed in greater detail elsewhere. However, it is clear that if superheated steam is used to fluidize an adsorbent solid, the heat transfer coefficient will be increased by adsorption-desorption processes, an equilibrium situation being reached so far as adsorbed water is concerned.

EXPERIMENTAL

The equipment used is illustrated in Figure 1 and consists of a pilot-plant dryer fitted with 90 electrically heated horizontal tubes 2.54 cm dia. on a triangular pitch of 5.08 cm. A number of the electrically heated tubes have been fitted with thermocouples embedded in the outer surface.

Several tubes have been replaced with tubes specially designed to allow estimation of the heat transfer coefficient from tube to bed. In each of these tubes, an electric element is mounted within a copper rod which has eight thermocouples silver soldered flush with the surface in various circumferential and axial positions. The copper rod has an outside diameter of 2.54

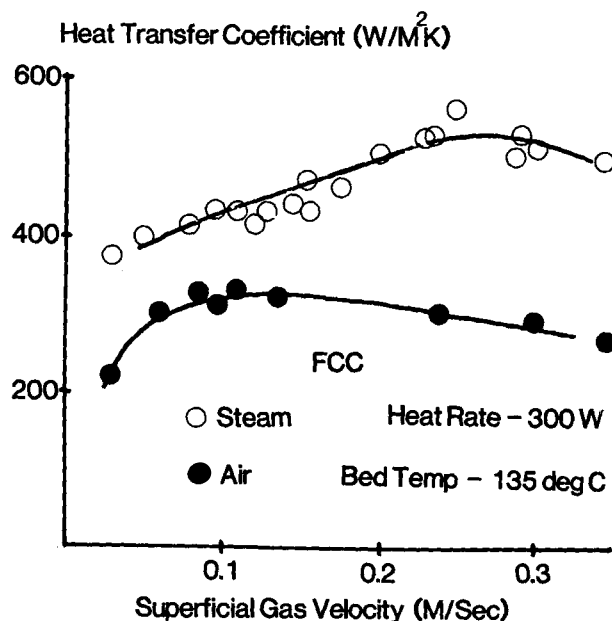
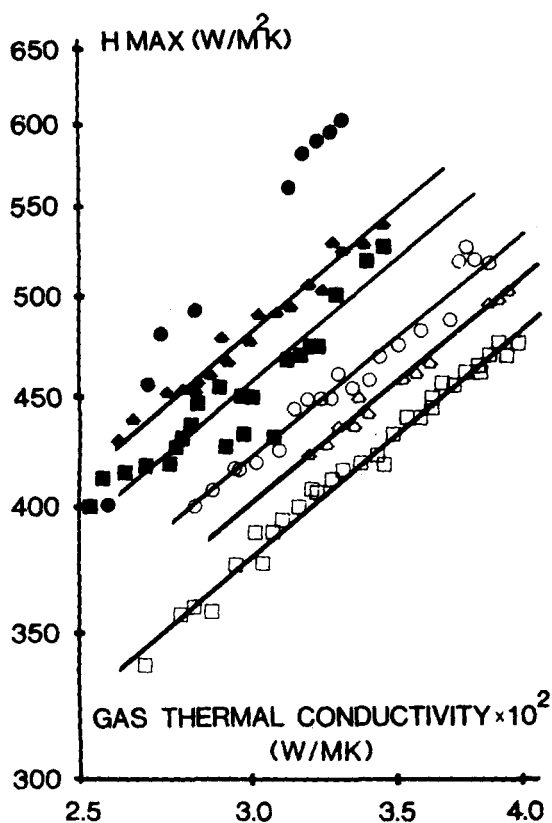


Figure 4. Heat transfer coefficient vs. superficial gas velocity for FCC with air or steam at constant heat flux and bed temperature.



KEY

	AIR	STEAM
SAND 1	□	■
SAND 2	△	◆
BALLOTINI	○	●
FCC	◻	◼

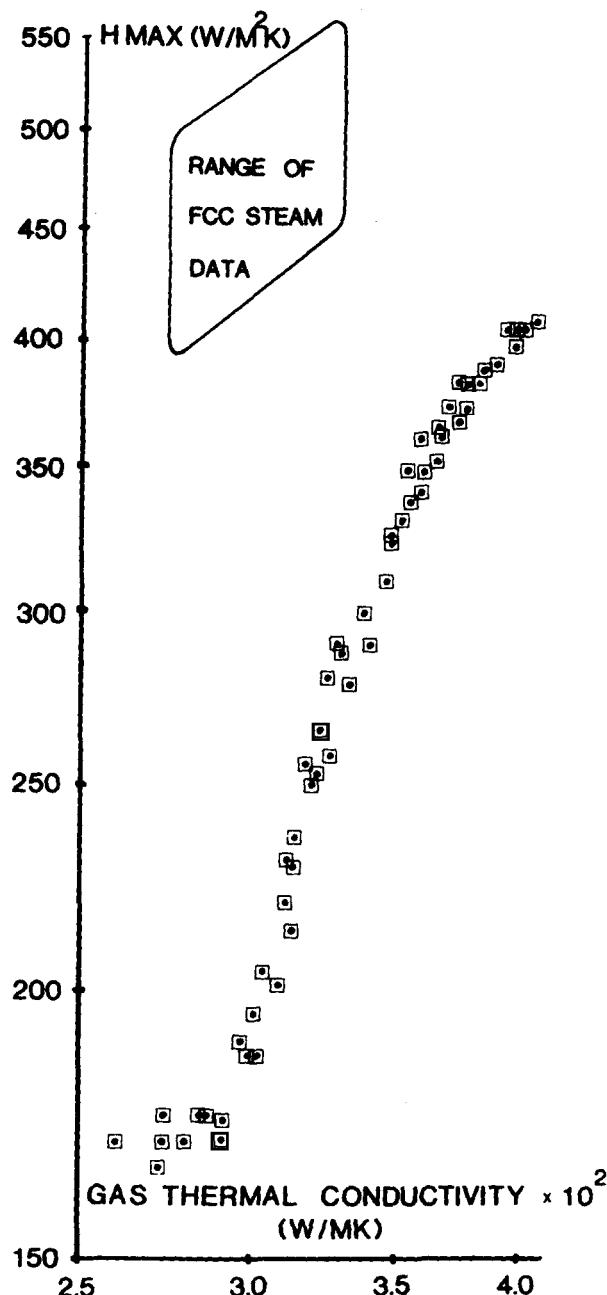


Figure 5. Maximum heat transfer coefficient as function of gas thermal conductivity, for Sand 1, Sand 2, ballotini and FCC with air or with steam.

cm and a surface area of 0.0212 m². The electric element has a diameter of 0.95 cm, so there is sufficient wall thickness to ensure a uniform surface temperature which is verified by the thermocouple readings. The tube is located in the bed by insulating teflon supporting rings. The power input to the element is measured using a dual coil wattmeter. Thermocouples are also located at various positions in the fluidized bed to allow determination of the bed temperature.

The fluidized bed is 30.5 cm² and is fitted with two cyclones in series, material captured by the first cyclone being returned to the bed. The body of the dryer is located in a hot gas enclosure, whose temperature can be adjusted to equal approximately the bed temperature. Most of the tubes in the bed can be used for heating the bed so that it is possible to vary both bed temperature and tube surface temperature as required, except that the process is always one in which the tubes heat the bed, appropriately to the drying situation.

Properties of the materials used are listed in Table 2. Both sands and FCC (fluidized cracking catalyst) fall into group A under Geldart's (1973) classification while the ballotini is just group B.

EXPERIMENTAL RESULTS AND DISCUSSION

Since bed temperatures ranged from 40 up to 200°C and tube temperatures to 280°C, there is a question as to the mean temperature to be used.

Figure 2, for FCC air, shows the maximum heat transfer coefficient as a function of: (a) bed temperature, (b) tube temperature, and (c) mean temperature calculated as the bed temperature plus 0.58 times the temperature difference. The mean of bed and tube temperatures is almost as successful in collapsing the data on a single curve and has been used on the grounds of simplicity. Zabrodsky (1973) earlier recommended a mean temperature closer to the wall (surface) temperature, but later Zabrodsky et al. (1976) employed the mean of tube temperature and bed temperature, in agreement with the above and also with Grewal and Saxena (1983).

Figure 3 displays the variation in heat transfer coefficient for Sand 1 and air, at a constant heat rate as a function of superficial velocity and bed temperature. The maximum heat transfer coefficient, h_{MAX} , increases with bed temperature as would be expected from the increase of the thermal conductivity of air with temperature and occurs at a velocity of between 0.3 and 0.4 m·s⁻¹.

Figure 4 shows similar data for FCC air and FCC steam, yielding values of gas velocity at which h_{MAX} occurs, of about 0.10 to 0.15 m·s⁻¹ for the former and 0.24 to 0.30 m·s⁻¹ for the latter. It is not obvious why the velocity for maximum heat transfer should change so much from air to steam, and this will require further investigation. It should be noted that steam yields much higher heat transfer coefficients than air.

Although not emphasized earlier, Figure 2 indicates that h_{MAX} for FCC air strongly depends on the mean temperature between tube and bed. The

correlations discussed earlier allow for variation of h_{MAX} with temperature through the effect of temperature on the gas properties' density, viscosity and thermal conductivity with the last being the dominant factor for Zabrodsky and Xavier and Davidson. If the variation of h_{MAX} with temperature is attributed wholly to the effect of temperature on gas thermal conductivity, we find, Figure 5, that for both sands with air and steam and ballotini with air, h_{MAX} is proportional to the appropriate gas conductivity raised to the power 0.84. Ballotini in steam shows a slightly higher dependence and FCC with air suggesting a very strong dependence.

The Zabrodsky equation obviously indicates a dependence on conductivity to the power 0.6, while for our sands in air and steam Xavier and Davidson's correlation suggests a dependency of 0.67. If the temperature variation of h_{MAX} from the Grewal and Saxena correlation is attributed wholly to gas conductivity, h_{MAX} would apparently vary with gas conductivity only to the power 0.4 over the range of temperatures used here.

It should be pointed out that nearly all the materials used in developing the above correlations would be classified as group B of Geldart (1973) whereas our sands are group A and the ballotini is fairly close to group A. As pointed out by Grewal and Saxena (1981b): "It has been well known and widely accepted that a correlation developed in a particular operational regime has only a doubtful validity in a different regime." Vreedenburg (1958) found the behavior of fine light particles sufficiently different from larger particles to warrant a separate correlation. More recently Hoelen and Stermerding (1981) have shown for powders which exhibit a dense-phase expansion, very strong dependence of the heat transfer coefficient on both the direction and magnitude of the temperature difference driving force. They clearly showed a contraction of the dense phase at a surface cooler than the bed and attributed the resultant lowering of coefficient to a reduction in particle mobility. Conversely at a surface hotter than the bed, dense-phase expansion occurred and a higher coefficient was evident. Hoelen et al. data for 40 μm FCC, with the tube heating the bed, showed an apparent dependence of h on air conductivity to the power 0.80.

Figure 5 also shows that for each material h_{MAX} in steam is higher than in air. This behavior is contrary to the predictions of all correlations and indicates that an extra mechanism of heat transfer may be operating when using steam. From the evolution of heat which occurs on admission of steam to a bed of air-dried FCC it is evident that moisture is adsorbed into the pores of the particles and the desorption of this moisture at the hot tube surface and consequent readsorption in the bulk bed could account for the higher heat transfer coefficient in steam over that in air. No explanation is given for the very consistent 20 to 25% increase in steam for the nonporous sands and ballotini, although capillary adsorption at points of contact may be a factor.

CONCLUSION

For fine relatively nonporous solids such as sand and ballotini, higher heat transfer coefficients are observed with steam than with air, contrary to the expected dependence of heat transfer coefficients on gas thermal conductivity. For such solids, dependence of h_{MAX} on k_g with an exponent of 0.84 is noted. No explanation is available for the higher coefficients in steam as compared with air, unless there is a greater adsorbency than expected, although at lower temperatures capillary adsorption at points of contact may be a factor. The behavior of cracking catalyst (FCC) is especially interesting. In air, the apparent dependence of h_{MAX} on gas thermal conductivity is much greater than an exponent of 0.84 would allow.

Explanations may lie in an apparent increase in heat capacity as a result of adsorption together with an additional mechanism associated with dense phase expansion.

NOTATION

Cp_g	= gas heat capacity, $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$
Cp_s	= particle heat capacity, $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$
D_T	= tube diameter, m
d_p	= mean particle diameter, m
g	= gravitational constant, $\text{m}\cdot\text{s}^{-2}$
h	= heat transfer coefficient, $\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$
h_{MAX}	= maximum value of h in plot of h vs. gas velocity, $\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$
k_g	= gas thermal conductivity, $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$
P	= tube pitch, center to center, m

ρ_p	= particle density, $\text{kg}\cdot\text{m}^{-3}$
ρ_g	= gas density, $\text{kg}\cdot\text{m}^{-3}$
μ_g	= gas viscosity, $\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$
Ar	= Archimedes number = $gd_p^3(\rho_p - \rho_g)/\mu_g^2$
Nu_{upm}	= Nusselt number based on h_{MAX} and $D_T = h_{\text{MAX}} D_T/k_g$

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