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Zonal heat transfer rates in a fluidized bed combustor

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Abstract—External heat transfer coefficients are reported for a horizontal water cooled coil located at different axial stations in a 0.6 m diameter atmospheric fluidized bed combustor. Comparisons of the heat transfer have been made with the combustor firing L.P.G. propane, anthracite, bituminous coal and pelletized waste derived fuel. It was found that the in-bed heat transfer coefficients were not sensitive to fuel type, fluidization velocity or bed temperature. The splash zone heat transfer, however, showed a strong dependence upon the nature of the fuel and the relative location of the coil.

1. INTRODUCTION

THE POTENTIAL of fluidized beds for burning a wide range of conventional and low quality fuels is well established and has been realized in the design of coal, gas, oil and solid waste firing combustion systems [1–4]. For multi-fuel fluidized bed boilers an efficient design relies to a significant extent on the correct sizing and disposition of heat transfer surfaces. This requires a detailed knowledge of heat absorption rates in different zones of the combustor, and, in particular, an appreciation of the way in which local heat transfer rates are influenced by the nature and properties of the fuel. The primary aim of the present study is to report values of heat transfer coefficients obtained from experiments on a 0.6 m diameter fluidized bed combustor firing L.P.G. propane, anthracite, bituminous coal and pelletized waste derived fuel (w.d.f.).

Horizontal water cooled coils were employed to measure the heat transfer in the in-bed region, splash zone and downstream region of the combustor removed from the splash zone.

The bulk of the previous work relating to heat transfer in fluidized beds has been concerned with the in-bed region since this is the source of the dominant heat transfer coefficients. Generally, unlike in this study, such work has been concerned with low temperature, non-reactive heat transfer neglecting combustion. Even under non-combustion conditions, an inspection of the major review studies [5–7] shows a diversity of empirically derived correlation equations for straightforward heat transfer geometries. Grewal and Saxena [8] investigated heat transfer to a single horizontal tube in non-reactive fluidized beds and have systematically correlated a wide range of data from their own experiments and elsewhere within a tolerance of ±25%.

2. EXPERIMENTAL EQUIPMENT

A representation of the 0.6 m diameter combustor is shown in Fig. 1. The construction comprised an internally tapered base section which housed 30 bubble cap type air distributor pipes, each containing six, 3 mm diameter efflux ports. A drain valve was located at the lowest point of the base section. Above the base section, the combustor was constructed from refractory lined, flanged, modular, standard sections of length 300 mm. Each modular section incorporated two access ports and three slots leading to the interior of the combustor. The latter were used to locate horizontally disposed stainless steel heat transfer coils and each had an effective heat transfer surface area of 0.32 m^2. The cooling coil slots were located at vertical intervals of 80 mm on the standard sections. Figure 2 shows the configuration of the coils. If a coil was not positioned in a slot then the slot was filled with a refractory plug backed by a steel plate.

The top section of the combustor supported a downward firing, long flame, nozzle mixing gas burner and also a horizontal outlet leading to a cyclone and flexible steel chimney. Measurements of gas composition were taken within the horizontal outlet section. Sand was used as the inert phase of the bed and for a 0.3 m bed depth the freeboard height to the flue outlet was approximately 1.2 m.

Start-up of the fluidized bed was achieved using a combination of the flame gases from the nozzle mixing burner and propane supplied from a gas manifold located in the first slot of the combustor lower modular section. The gas manifold comprised one of the heat transfer coils drilled with 169, 0.8 mm diameter upward facing holes and it was positioned at a distance 80 mm above the top of the bubble cap distributors. The post mixed ignition procedure allowed

NOMENCLATURE

D_b	effective bubble diameter [m]	L	location of heat transfer coil relative to static bed surface [m]
F_0	fuel feed rate [$\mathrm{kg\,s^{-1}}$, $\mathrm{kg\,h^{-1}}$]	T_B	bed temperature [K]
h	heat transfer coefficient corrected for water side heat transfer (external heat transfer coefficient) [$\mathrm{W\,m^{-2}\,K^{-1}}$]	U_B	bubble rise velocity [m]
		U_f	fluidization velocity [$\mathrm{m\,s^{-1}}$]
H_f	fluidized bed height [m]	U_{mf}	minimum fluidization velocity [$\mathrm{m\,s^{-1}}$]
H_{mf}	bed height at minimum fluidization [m]	w.d.f.	waste derived fuel [—].

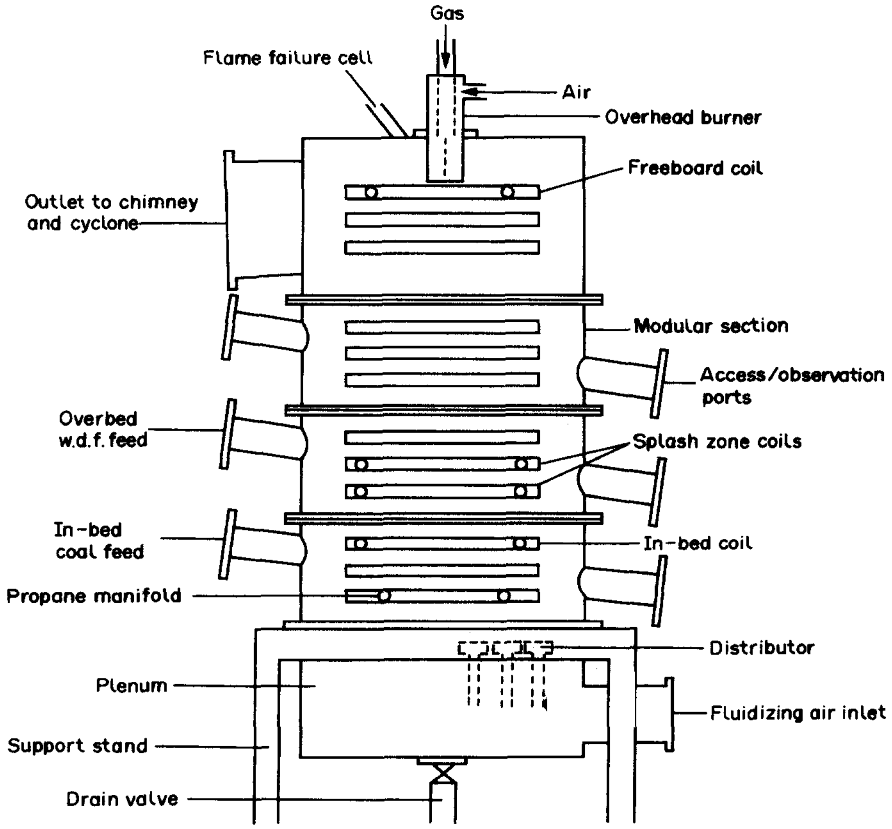

FIG. 1. 0.6 m diameter fluidized bed combustor.

a sand of 130 kg to attain a bed temperature of 700°C in approximately 30 min.

In the case of solid fuel firing, anthracite and bituminous coal were injected into the base of the sand bed using a rotary metering valve. Waste derived fuel pellets, obtained from the Chichester plant, were propelled onto the surface of the fluidized sand bed by means of a pneumatic piston. Metering of the fuel flow rate was achieved with the aid of a screw feeder.

Instrumentation included platinum resistance thermometers for the measurement of cooling water inlet and outlet temperatures, gap meters for the measurement of cooling water flow rates, an orifice plate for the measurement of fluidizing air flow rate and rotometer for the measurement of propane flow rate. Average bed and freeboard temperatures were determined by means of four platinum/platinum rhodium thermocouples spaced along the axis of the combustor. Concentrations of O_2, CO_2 and CO were found using paramagnetic and infra-red gas property sensing instruments. Data logging equipment was used to monitor the temperature responses of the various thermocouples.

3. EXPERIMENTAL CONDITIONS

Table 1 gives the size distribution and mean size of the inert phase of the bed material. Static sand bed depths ranged from 0.3 to 0.34 m and the minimum fluidization velocity of the cold bed was 0.14 m s^{-1}.

The mean size of the bituminous coal and anthracite was 1.92 mm. As received, the waste derived fuel pel-

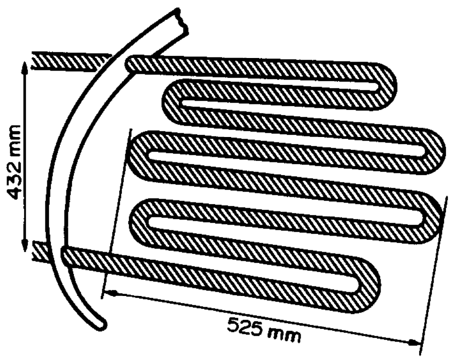

FIG. 2. Heat transfer coil.

lets were cylinders of nominal length 50 mm and diameter 15 mm. Some slight yet variable size degradation of the pellets occurred in the rotary screw section of the pellet feeder. Table 2 gives the proximate analysis of the solid fuels.

The first step in the experimental procedure was to select the location of the heat transfer coils. Experience showed that a strong coupling between in-bed and splash zone heat transfer would not allow operation with coils in the two zones during a single experiment since a steady-state bed temperature could not be maintained. Thus splash zone and in-bed heat transfer rates were found from separate experiments. In all cases, however, a coil was located in the upper slot of the top modular section of the combustor. This coil was modified in shape and reduced in size to prevent the impingement of flame gases from the overhead burner.

Bed start-up was initiated by ignition of the overhead burner to warm the interior of the combustor and then gas was supplied from the propane manifold. When the bed achieved a temperature of approximately 700°C, the overhead burner was turned off and feeding of the selected fuel commenced. In the case of propane firing the fuel continued to be supplied from the lower manifold. During the heat transfer measurement experiments, the fuel flow rate was maintained at a constant value and fluidization velocity (hence excess air) was varied in increments. Careful observations on the extent of combustion quality were made in this procedure by reference to the gas analysis instruments. Following an alteration in fluidization velocity steady-state conditions were attained after about 20 min. Water temperature elevations at the different coil locations ranged from 40 to 80°C.

Overall heat transfer coefficients were calculated from the water temperature rises and these were then corrected to give the external heat transfer coefficients (h) using well-known methods.

4. RESULTS

Figures 3–6 exhibit the external heat transfer coefficients for each of the four fuels tested. Values are compared on the graphs for coil locations of $L = -130$, 80 and 910 mm from a static bed height of 0.3 m ($L = 0$ mm). Also included are the bed temperature, T_B, mean freeboard temperature, T_F, and combustion quality assessment for conditions in approximate correspondence to the optimum combustion performance with a coil located at $L = -130$ mm and excess air level. Heat transfer results for propane in Fig. 4 at $L = 120$ mm were obtained with a static sand bed height of 0.34 mm. The use of non-dimensional fluidization velocity has been necessitated by the need to make the velocities independent of temperature since the manometric liquid levels are often unstable at bed temperatures. However, by making use of gas densities at both cold and hot bed temperatures, the minimum fluidization velocity, U_{mf}, is calculated to be 0.48, 0.52 and 0.55 m s^{-1} at temperatures of 983, 1030 and 1127 K, respectively, when U_{mf} for the cold bed is 0.14 m s^{-1}.

5. DISCUSSION OF RESULTS

Inspection of Figs. 3–6 shows only minor variations of the in-bed heat transfer coefficients ($L = -130$ mm) with fluidization velocity and fuel type. The overall spread of results from the mean over the entire

Table 1. Size distribution of bed material

Size (μm)	2360	1700	1180	850	600	425	300	212	150	106	75
Mass (%)	0.001	0.002	0.003	0.003	4.10	52.5	40.7	2.5	0.18	0.006	0.003

Table 2. Proximate analysis of solid fuels (as received)

Fuel	Percentage moisture (%)	Percentage ash (%)	Percentage volatile matter (%)	Percentage fixed carbon (%)	G.C.V. (MJ kg^{-1})
Anthracite					
Source: Onllwyn	2.7	3.4	9.2	84.7	34.2
Bituminous coal					
Source: Rawdon	10.7	3.5	35.7	50.1	28.6
Waste derived fuel	6.3	21.7	58.4	13.6	14.7

G.C.V. of propane = 49.8 MJ kg^{-1}.

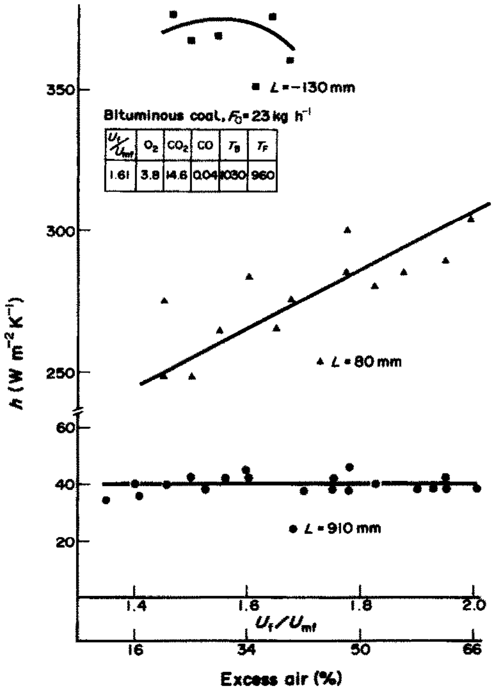

FIG. 3. Heat transfer characteristics of a bituminous coal-fired fluid bed.

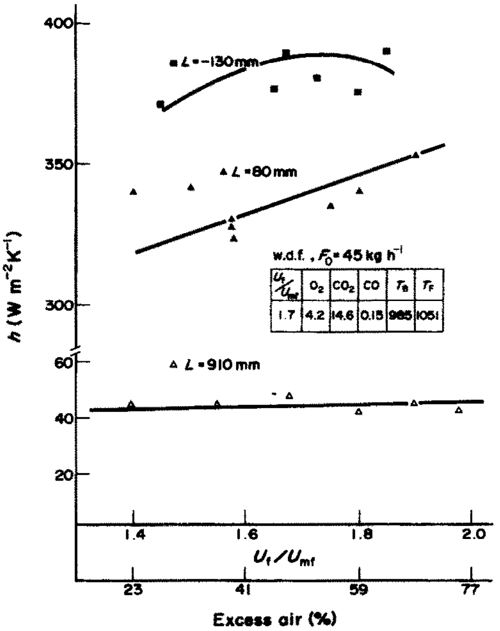

FIG. 5. Waste derived fuel-fired fluidized bed heat transfer characteristics.

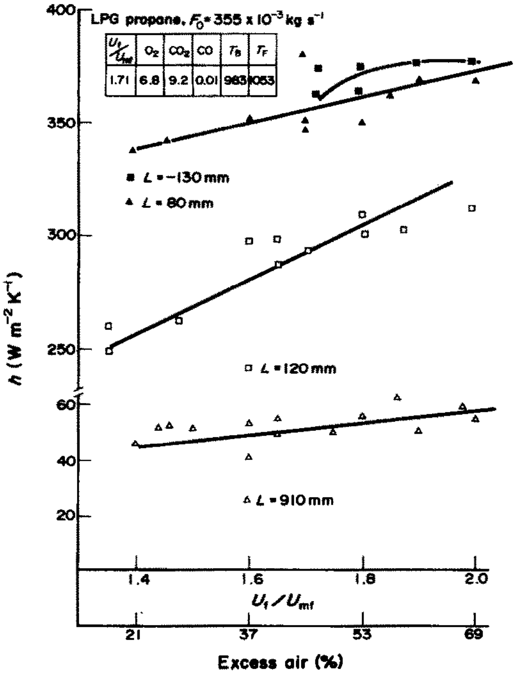

FIG. 4. Heat transfer coefficient in a propane-fired fluid bed.

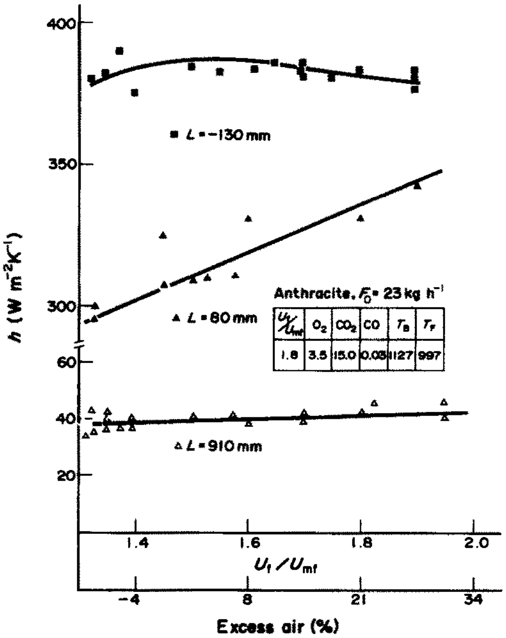

FIG. 6. Heat transfer coefficient in an anthracite-fired fluid bed.

range of fuels and fluidization velocities was 20 W m^{-2} K^{-1} and therefore it can be said that, for practical purposes, the in-bed heat transfer coefficients are independent of fuel type and fluidization velocity. The bed temperatures included on the graphs show that the values for w.d.f. and propane are not significantly less than those for anthracite and bituminous coal. A consequence of the above observations is that the in-bed heat transfer coefficients are not sensitive to bed temperature for the range of conditions considered.

The finding does not agree with the results of Grewal and Hajicek [9] who found a strong dependence of the heat transfer on bed temperature in their experiments using low rank coals and a staggered array of immersed horizontal tubes. The reason for the low bed temperatures in the w.d.f. and propane firing trials was the after-burning of volatile gases and propane on the bed surface and in the freeboard region. Table 2 shows that the volatile matter content of w.d.f. was 58.4%. The combustion quality assessment reported in Fig. 5 indicates a poor combustion performance for w.d.f. due, amongst other factors, to the low bed temperatures provided by an oversized heat transfer coil. The bed temperature could be increased by firing more w.d.f. but this was not done as it would lead to a further increase in freeboard temperature. In contrast the combustion assessments for propane, anthracite and bituminous coal are adequate and appear to conform to accepted practice.

The results for the variation of the heat transfer coefficients with fluidization velocity show two distinct trends. The first trend involves substantially constant values of the heat transfer coefficient with increasing fluidization velocity. In general, this relates to in-bed heat transfer in the downstream region of the combustor removed from the splash zone ($L = 910$ mm). The second trend concerns a linear increase in the heat transfer coefficient with increasing fluidization velocity.

The effect is associated with heat transfer at $L = 80$ and 120 mm but, at $L = 80$ mm it is significantly more prominent for bituminous coal and anthracite than in the case of propane and w.d.f. Of particular interest in Figs. 3–6 is the relative values of the heat transfer coefficient at $L = 80$ mm for each fuel. Also, for propane, the sensitivity of the heat transfer coefficient to coil position at $L = 80$ and 120 mm is demonstrated in Fig. 4.

Contrary to Gelperin and Einstein [5], Priebe and Genetti [10] in their experimental studies, did not find a maximum but a monotonic increasing heat transfer coefficient with superficial velocity. This disagreement, apparently, may be explained by the findings of this study. An examination of each of the graphs shows that the in-bed heat transfer results have a peak in agreement with Gelperin and Einstein whereas the splash zone data corroborate those of Priebe and Genetti by exhibiting linearity with increasing superficial velocity. However, the experimental results of Chakraborty and Vickers [11] appear to agree with the present investigation both in peaking and linearity of heat transfer data in the in-bed and splash regions, respectively.

The effects summarized above for the downstream near bed region are related in an undetermined way to (i) an expanded bed height which is difficult to define, (ii) bed by-passing characteristics of air and volatile components, (iii) frequency and magnitude of surface bubble eruptions, either supported or not supported by combustion, and (iv) the presence or absence of flame at the bed surface.

6. CONCLUSIONS

(1) Within the range of conditions $1.24 < U_f < 1.77$ m s^{-1}, $938 < T_B < 1163$ K, $d_p = 360$ μm in-bed external heat transfer coefficients were found to have no significant, systematic dependence upon the type of fuel, fluidization velocity or bed temperature.

(2) For the 'volatile' fuels (propane and w.d.f.) constraints were imposed on the realizable bed temperature due to an oversize heat transfer coil and after-burning of combustible gases on the bed surface and in the freeboard region. It may be surmized that in the case of w.d.f., the reduced bed temperature was a cause of the poor combustion performance of the fuel.

(3) Heat transfer coefficients in the near bed downstream region of the combustor were found to be strongly dependent upon the type of fuel, and, in the case of propane, to heat transfer coil location. A proper interpretation of these results requires an examination of what is meant by splash zone heat transfer for the conditions considered.

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FLUX THERMIQUES ZONAUX DANS UN FOYER A LIT FLUIDISE

Résumé—Des coefficients de transfert de chaleur externe sont donnés pour un anneau horizontal refroidi à l'eau, placé à différentes positions axiales dans un foyer atmosphérique à lit fluidisé de 0,6 m de diamètre. Des comparaisons sont faites avec des foyers à propane GPL, anthracite, charbon bitumeux et des boulets de déchets dérivés du pétrole. On trouve que les coefficients de transfert interne au lit ne sont pas sensibles au type de combustible, la vitesse de fluidisation ou la température du lit. Néanmoins le transfert dans la zone d'étalement montre une forte dépendance vis-à-vis de la nature du combustible et de la position relative de l'anneau.

WÄRMEÜBERTRAGUNG IN DEN EINZELNEN ZONEN EINER WIRBELSCHICHT-BRENNKAMMER

Zusammenfassung—Es wird über den Wärmeübergang außen an einer horizontalen wassergekühlten Rohrschlange berichtet, die axial an verschiedenen Stellen in einer atmosphärischen Wirbelschicht-Brennkammer mit 0,6 m Durchmesser angeordnet ist. Die Wärmeübergangsbedingungen bei Beheizung der Brennkammer mit Propan, Anthrazit, bituminöser Kohle und pelletisiertem, aus Abfallprodukten gewonnenem Brennmaterial wurden verglichen. Es wurde herausgefunden, daß die Wärmeübergangskoeffizienten im Wirbelbett weder vom Brennstofftyp noch von der Fluidisations-Geschwindigkeit oder von der Bettemperatur abhängig waren. Im Spritzbereich zeigte der Wärmeübergang jedoch eine starke Abhängigkeit von der Beschaffenheit des Brennstoffs und von der relativen Position der Rohrschlange.

ИНТЕНСИВНОСТЬ ТЕПЛООБМЕНА В РАЗЛИЧНЫХ ЗОНАХ ТОПКИ С КИПЯЩИМ СЛОЕМ

Аннотация—Представлены коэффициенты внешнего теплообмена для горизонтального охлаждаемого водой змеевика диаметром 0,6 м, располагаемого в различных позициях по оси топки с атмосферным псевдоожиженным слоем. Сравнивался теплообмен в топках, сжигающих сжиженный нефтяной газ, антрацит, битуминозный уголь и окомкованные отходы топлива. Найдено, что коэффициенты теплообмена внутри слоя не зависят от типа топлива, скорости псевдоожижения или температуры слоя. Вместе с тем, показана сильная зависимость коэффициентов теплообмена от рода топлива и относительного расположения змеевика в подслоевом пространстве.