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COMPOUND HEAT EXCHANGE BETWEEN A HIGH TEMPERATURE GAS-FLUIDIZED BED AND A SOLID SURFACE

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Abstract—Heat transfer of a surface "wetted" by a fluidized bed at elevated temperatures is considered. The variable role of the radiative component of transfer is discussed. The conditions of both additivity and non-additivity of heat transfer components are indicated and also the conditions of replacement of non-radiative component by the radiative one. Considerations are presented about selection of the so-called "limiting" temperature. Results of determination of the fluidized bed effective emissivity are discussed.

NOMENCLATURE

D, diameter of solid particle;
h, film heat transfer coefficient, apparent value based on $(t_{bb} - t_w)$;
k, thermal conductivity;
L, distance between solid particles;
m, porosity (void fraction) of bed;
m', $(1 - m)^{-\frac{1}{3}}$;
N, relative fluidization velocity (ratio of superficial velocity of gas to minimum fluidization velocity);
s, $\tau v_g/m$;
t, temperature;
T, absolute temperature;
U, over-all heat transfer coefficient;
v, superficial (nominal) velocity;
ϑ, $(1/m')^2$;
τ, time of exposure of a solid particle to heat transfer surface (wall).

Subscripts

b, bed;
bb, bulk of bed;
dev, developed (at high N values);
g, gas;
max, maximum value;
nr, non-radiative component;
r, radiative;
s; solid material;
t, total value;
w, wall, heat transfer surface.

In PREDICTING high-temperature gas-fluidized systems one has often to face the problems of compound heat transfer, when there is simultaneous thermal radiation, conduction and convection. These are the heat transfer problems of surfaces "wetted" by fluidized beds.

Heat transfer by thermal radiation is known to play an important role for effective conduction of heat in fixed high-temperature beds of solid particles and, hence, in beds with minimum fluidization when there is no significant motion of solid particles, that is at the onset of fluidization. In normal bubbling fluidized beds, however, the contribution of the radiative component, compared to heat transfer by fast moving solid particles, is quite insignificant [2].

On the other hand, the radiative component should be accounted for in heat transfer between a high temperature fluidized bed and immersed bodies or confining walls when the temperature of the bed or the body (wall) is rather high [2, 3].

It should be noted here, that up to now some authors [9] support the reverse opinion [7, 8] that there is no significant radiant heat transfer in high temperature fluidized beds, which was later discarded by the authors of [7, 8] who originally had justified it putting forward the following considerations:

1. Heat cannot be transferred by radiation between a fluidized bed and a body, just like between a flow of a nondiathermic liquid and confining walls.

2. Up to about 1000–1100°C the maximum overall bed-to-surface heat transfer coefficient $h_{t\,max}$ proved to be a linear function of temperature.

3. Aluminium bodies, having low emissivities, can be preheated in fluidized beds nearly as fast as steel bodies.

It has been proved [5] later, however, that the fluidized bed-liquid analogy disregards the fact that in any normal bubbling fluidized bed there are significant temperature differences between a wall (a body) and adjacent solid particles which is not the case with liquid flows and non-stirred granular beds descending by gravity along vertical walls. Radiative heat transfer is not even excluded in the "worst" case, when a layer of adhered solid particles is formed on the confining walls, being only displaced to the interface between fixed and moving parts of the bed. Here, by the way, the effect of the wall emissivity would be to some extent diminished.

The author of [5] was also able to explain the "anomalies" mentioned under 2 and 3.

To summarize, there is a kind of displacement by radiation of $h_{t\,max}$ of the non-radiant heat transfer component with the result, that up to temperatures about 1400°K the maximum overall heat transfer coefficient $h_{t_{max}}$ remained to be fairly equal to the purely non-radiant one, which could have been obtained with ideal wall reflectivity. Hence, there is an approximately linear dependence of $h_{t\,max}$ on temperature, as shown in [7, 8], and the possibility [5] of its calculation, under such conditions, by simple empirical equations of non-radiant fluidized bed-to-surface heat transfer.

But such "simplicity" provides no sound reasons to ignore actual existence of radiant component of heat transfer in high-temperature fluidized beds. The account for this fact becomes indispensible for developing new improved units employing such beds [6, 10].

Let us now consider the conditions at which a radiant component in heat transfer by a fluidized bed is much weaker than it would be at first sight expected from [2] or judged by high radiant heat fluxes to probes [11, 25].

First, it applies to the case when solid particles (or their groups, the so-called "packets") very slowly replace one another at a heat exchange surface (wall). Under such conditions, the heat transfer coefficient, calculated usually by the temperature difference between the wall and the bulk of bed, represents an overall, rather than a film, value due to two thermal resistances connected in series: a "contact" resistance of a gas film at the wall and resistance of the packet itself. It is usually assumed here, that a radiative heat flux across the packet may be neglected. However, radiation diminishes the "contact" resistance of a gas film acting in parallel with conduction and convection.

It is evident that with slow replacement of packets and their high thermal resistance any change in the radiative component of the film-heat-transfer coefficient from a high value to the very high one provides only a small increase in the heat flux. This means, that the temperature of slowly moving solid particles during their prolonged exposition at the wall becomes nearly equal to the wall temperature and both the radiative and non-radiative heat fluxes drop to an extremely low level, while the effective h_r, based on the temperature difference between the wall and the bulk of the bed, becomes many times smaller than the true one (h_r'), based on a small and unknown temperature difference between the wall and a row of solid particles adjacent to it. This true h_r' is easily to be predicted but, unfortunately, it is useless for design calculations.

With large enough expositions, when a temperature increment of particles, adjacent to the wall, becomes commensurable with a temperature head between the wall and the bulk of the bed $(t_w - t_{bb})$, a non-linear dependence of Δt_s on time shows itself. Then components of the film-heat-transfer coefficient become non-additive in the sense that the total Δt_s at the prescribed time of particles exposition at the wall will be somewhat less than the sum of partial increments, calculated for individual components. Under such conditions, each of the components of a heat flux, adding itself to the remainder, tends to diminish their values by displacing the overall process to the region of smaller average temperature heads between the wall and the first row of particles [2].

As compared to the additivity, here in the first place we have a real mutual weakening rather than a replacement of one component by the other.

For the conditions of slow motion of solid particles, there is, in principle, a possibility, as shown in [13] to calculate the radiative contribution to heat exchange by using a step-by-step method for a certain prescribed average thickness of a gas layer between the wall and a packet. But for the present, no direct methods of measuring this thickness and its dependence on different parameters are available.

For a high-temperature normal bubbling fluidized bed with fast moving solid particles a temperature increment Δt_s during particles exposure at the wall and the thermal resistance of the bed itself become very small. Then the representation of h_t as an over-all heat transfer coefficient falls out and the achieved values of the maximum film-heat-transfer coefficient $h_{t\,\max}$ and the contributions of various components may be judged only from the considerations that in ordinary high-temperature fluidized beds, in contrast to low temperature ones [14], the maximum heat transfer operation conditions correspond to high effective porosities of a bed. In other words, $h_{t\,\max}$ is achieved upon passing the $h_{nr\,\max}$.

Here is the reason why the total film heat transfer coefficient at high velocities of gas

$$h_{t\,dev} < h_r + h_{nr\,\max}. \tag{1}$$

The other inequality holds too

$$h_{t\,\max} < h_{nr\,\max} + h_{r\,\max}. \tag{2}$$

The latter inequality has been suggested in [5] proceeding from an idea that $h_{r\,\max}$ and $h_{nr\,\max}$ do not coincide, as h_{nr} alone is very sensitive to bed porosity, m, and is in reverse dependence on it [2], that is why h_{nr} reaches its maximum value at "modest" values of m. As for h_r, it increases with increasing bed porosity, when the wall will "see" better not only the adjacent somewhat cooled solid particles but more distant and hot ones. Here, it is tacitly assumed that a sufficient optical thickness of the bed is easily provided.

While the velocity of particles increases with a gas rate, a monotonous, gradually slowing down and sometimes small, increment of h_r may be expected. This may result in more flat maxima of h_t for high-temperature fluidized beds, compared to low-temperature ones, and redistribution of h_r and h_{nr} will evidently occur: with increasing gas velocity a radiant component of heat transfer will gradually replace a non-radiant one. Here, when $\Delta t_s \ll (t_w - t_{bb})$, there is no appreciable mutual weakening of components and they may be considered additive.

Since in a normal bubbling fluidized bed $h_{nr\,\max}$ can be achieved at "modest" h_r (effective values of it based on $T_{bb} - T_w$), there is nearly a linear dependence of $h_{t\,\max}$ on the controlling temperature and the numerical values of $h_{t\,\max}$ may approximate $h_{nr\,\max}$.

By the way, this linear dependence testifies to the presence of a radiative component in $h_{t\,\max}$, rather than to its absence, as for non-radiative $h_{nr\,\max}$ the temperature dependence is much weaker. Indeed, $h_{nr\,\max} \sim k_g^{0\cdot6}$, as shown in [2]. The value k_g is proportional to $T^{0\cdot75}$ in the range 400–1300°K for gases used in the pertaining experiments [7, 8].

The above and the considerations presented in [2] suggest, that higher values of $h_{t\,\max}$ can in principle be obtained in high-temperature fluidized beds than the values hitherto obtained. This increase can be achieved by an artificial fast movement (for example, mixing) of a bed provided that there is no increment of porosity at the body surface "wetted" by a fluidized bed. In such an ideal case, the temperature of the solid particles, adjacent to the surface, equals that of the bulk of the bed and the following equation holds

$$h_{t\,\max} = h_{nr\,\max} + h_{r\,\max}. \tag{3}$$

Unfortunately, there is a barrier to attaining such high heat transfer rates in separation of fluidized beds from the immersed tubes, an effect known already since [2]. The effect is present and becomes even more pronounced at high relative velocities of solids past tubes, greatly affecting the limiting value of $h_{t\,\max}$.

Later on, J. S. M. Botterill *et al.* [15–17] also pointed to separation of a fluidized bed from tubes but notwithstanding attempted to achieve especially high heat transfer rates ($h_{nr\,\max}$) in fluidized beds utilizing an arranged horizontal flow of fluidized solids past tubes with relative velocities up to 0·3 m/s. As reported in [18], this attempt was not advantageous, which is quite natural, if only because conventional cylindrical tubes were employed.

Development of fluidized-bed heat exchangers with a non-separating flow seems to be a rather complicated task.

Perhaps it would be better to benefit from the advantages of radiant heat transfer from a high-temperature fluidized bed by developing effective radiative (or radiative-conductive) heat exchangers [6] with a diluted fluidized bed, noted for its low drag. Indeed, as previously mentioned, the maximum radiant fluxes from a high-temperature fluidized bed can be attained at high gas flow rates. A uniformly diluted fluidized bed displays high effective emissivity. However, its realization in commercial units by a simple increase in a gas flow rate is obstructed by development of large bubbles with the result of a heavy carry-over of solids from a bed. As it has already been done in the well-known experiments of Mickley and Trilling, such a situation can be cured by a return of the entrained particles. However, this approach seems to be less attractive when dealing with burning-hot solids. In lieu, it is much easier to make use of the known effect of internals on bed expansion providing that for such internals the heat transfer elements themselves are taken [6].

It should be further noted, that employment of high fluid flow rates permitting realization of large radiant fluxes in high-temperature systems is especially profitable when a fluidized bed itself is at an elevated temperature while a wall (surface) is cooled to a rather low temperature by water or organic liquids. Then the values of h_r remains almost independent of the low wall temperature when solid particles move fast to and from the wall. At the same time it is known [19], that such systems have rather "modest" values of h_{nr} at very high temperatures of the bed owing to low thermal conductivity of the gas sub-layer at the wall.

Indeed, it follows from [2] that $h_{nr\,\max}$ between a high-temperature fluidized bed and a cold surface must be lower than that between the same bed and a hot surface, due, primarily, to the difference in average temperatures and thermal conductivities of gas layers at one surface and the other. For instance, with equal absolute values of a temperature head $|\Delta t|$ this temperature is about $(t_{bb} - |\Delta t|)/2$ for a cold surface and $(t_{bb} + |\Delta t|)/2$, for a hot one.

However, the calculations, presented in [14] and [19], revealed that better correlation of experimental data is achieved when for the "limiting" temperature a value, much closer to the wall (surface) temperature, is taken rather than an arithmetic mean value, mentioned above. This may be attributed to a gas flow through a fluidized bed, which is usually neglected [20]. It is true, that low specific heat and high thermal diffusivity of a gas testify against our supposition of "rebuilding" of temperature fields by a gas flow as compared to the fields calculated in [20] for a static gas. But in view of the data obtained by Korolev and Syromyatnikov [21], indicating that there is a kind of a gas breakthrough along vertical plates, "wetted" by a fluidized bed, a greater influence of a gas flow may be expected. For the period of particle exposure at a surface, gas volume in the zone of an intense heat flow to or from a particle will be replaced hundreds, if not thousands, of times. Besides, the temperature of a gas coming to a point of contact (or to a place of maximum approach of a particle to the surface) will be about that of the surface. But no quantitative estimation has yet been made of the above.

The effect of the so-called "temperature factor" [19] or heat flow direction (from the bed to the wall and vice versa) reduces to the role of the limiting temperature, mentioned above.

Let us now return to inequality (2). It suggests that on subtracting the values of $h_{nr\,\max}$ (whatever exact) from the experimental values of $h_{t\,\max}$, underestimated, rather than real values of $h_{r\,\max}$, are obtained. Under $h_{t\,\max}$ conditions, the difference $(h_{t\,\max} - h_{nr\,\max})$ is even less than h_r, as $h_{nr\,\max}$ is not attained at these conditions.* None the less, this difference or, based on it, any other measure of disturbance in the "low temperature dependence" of $h_{t\,\max}$ on k_g may present a certain practical interest for estimating a correction factor for radiation. It is by this factor that the value of $h_{nr\,\max}$, obtained from the "basic" equation, is to be multiplied to give the total value of $h_{t\,\max}$, which incorporates a radiant component. Evidently, the difference $(h_{t\,\max} - h_{nr\,\max})$ and the correction factor will also depend on the selected "limiting temperature" which in its turn defines the physical constants applied in calculating $h_{nr\,\max}$. Such a correction factor has been calculated in [14] to describe experimental data on heat transfer by a fluidized bed from a high temperature surface. There, the wall temperature has for simplicity been taken for the limiting temperature. It is quite natural, that the correction factor proved to be higher for beds of large solid particles, rather than fine, as the former have smaller $h_{nr\,\max}$ [2] which increases relative contribution of radiation. This statement seems to be inconsistent with the recent findings of Szekely and Fisher [22], who conclude that the role of radiation in the total heat transfer between a surface and a fluidized bed increases with increasing time of particles exposure at the surface and decreasing diameters of particles. This conclusion is a correct one, but rather trivial. It could have been drawn from elementary considerations on asymptotic increase in h_r when the temperature of a radiator and that of a receiver (detector) are approaching each other. This approach is certainly favoured by using small solid particles and prolonged exposures at the surface. But under such operating conditions there are negligible radiant and total heat fluxes which make the conditions inapplicable in conventional heat exchangers.

In contrast, the author made investigations of, and conclusions on, the conditions of intense heat transfer.

Finally, we shall consider the problem of estimating the fluidized bed emissivity ε_b. It is essential in compound heat transfer calculations, unless we confine ourselves to employing an empirical correction factor for radiation.

Evaluation of ε_b of a dense granular bed (including a dense phase of fluidized beds) may be approached as a problem of calculation of ε for a flat surface of material with the known number of hollows corresponding to pores between particles. Note, that the main portion of the surface of solid particles, "seen" by the wall, is located nearly in the plain of the wall rather than deep in pores where ε approaches unity. Such a distribution of a radiating surface of a bed gives evidence to the possibility for the values of ε_b to be considerably less than unity at low ε_s of the solid material itself. That is why, the method of calculating ε_b, suggested by Rubtsov and Syromyatnikov [23] and based on estimation of a fraction of the wall surface, "overshadowed" by the first (ϑ_1) and the following rows of particles, turned to be a better approach than that with application of Buger's law. The authors of [23] demonstrated that sometimes

* Not suspecting it, the authors of [24] have confirmed this fact by their calculations described in [24].

ε_b must really be much less than unity. However, they did not justify the basic expression $\vartheta_1 = (1/m')^2$, where $m' = (1 - m)^{-\frac{1}{3}}$. In principle, even for a regular bed of identical spherical particles ϑ_1 must depend on the type of packing.

For instance, for a simple loose cubical packing the interparticle distance would be [2]: $L = 0{\cdot}807d\cdot(1 - m)^{-1/3}$ and $\vartheta_1 = \pi D^2/4$, $L^2 = 1{\cdot}7\,(1/m')^2$ rather than $(1/m')^2$. As has been noted in [11], in a real case of packets (groups) of particles of a mixed size even a greater deviation from the model, assumed in [23], is possible being directed towards increasing ϑ, and decreasing effective ε_b.

It should be noted, that elevated temperatures require employment of refractory and wear-resistant bed materials like pure metal oxides (Al_2O_3, ZrO_2, MgO_2, etc). Their emissivities are low and so a deviation of ε_b from unity must be pronounced over rather a wide range of conditions.

In [11] the measurements of the effective fluidized bed emissivity are described. Some of the results are shown in Table 1, which testifies to a strong enough dependence of ε_b on ε_s of the solids. The experimental conditions did not reveal the influence of the remaining variables such as the temperature of a bed, the size and the shape of particles and relative fluidization velocity on ε_b values.

The minimum ε_b has been attained for beds of pure metal oxides (Al_2O_3, ZrO_2) whose ε_s are low and about equal. It is an interesting fact, ascertained by specially performed runs [11], that contamination of the surface of corundum particles by iron oxides sharply increases (up to $\varepsilon_b = 0{\cdot}9$) the emissivity of a fluidized bed of corundum.

An apparent lack of dependence of ε_b on the relative velocity of fluidization (see Table 1) is primarily attributed to the design of the probe used. Its detailed description is given in [4]. The receiving part of this probe was protected from particles of the bed by a thin quartz optical glass fixed by a water-cooled annular nut. When explaining the experimental results measured with such a probe, the authors of [11] have put forward [25] a suggestion that the protective glass was poorly cooled and its temperature approached that of the bulk of the fluidized bed, so whatever regime existed of the developed fluidization, the temperature of the solid particles, exposed at the protective glass, did not change significantly and the radiant flux was not reduced by cooling the first row of particles in contrast to the case of an ordinary actively cooled surface immersed in a fluidized bed).* Thus such a probe does not permit measurements of an apparent

Table 1. *Experimental results of* [11]

Material of bed	D (mm)	N	t_{bb} (°C)	ε_s	ε_b
1. Molten magnesite compound of MgO and SiO_2 (irregularly shaped particles)	1–1·5	1·2–3·0	500–1200	—	0·95
2. River sand (rounded particles)	1–1·5	1·2–3·0	500–1100	0·60	0·85
3. Chamotte (irregularly shaped particles)	1–1·5	1·2–3·0	450–1100	0·60	0·80
4. Zirconium dioxide ZrO_2 (rounded particles)	0·25–1	1·2–4·0	600–1150	0·23	0·59
5. Corundum Al_2O_3 (rounded particles)	1·5–2	1·2–3·0	800–1450	0·27	0·59

* Recent simple calculations performed by Baskakov and Goldobin [24] have confirmed this ill-cooling of the protective glass [25].

bed emissivity which incorporates hard-to-measure nonisothermity of a fluidized bed close to an actively cooled or preheated wall (surface).

But it is this apparent emissivity ε_b, in terms of which it is easier to calculate the radiant fluxes in heat exchangers when the temperature of the wall (tubes) and that of the bulk of the bed are given.

That is why it is essential now that radiometers with a controlled temperature of protective glass be designed which would make it possible to reveal the quantitative dependence of apparent ε_b on different variables.

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ECHANGE THERMIQUE COMPOSE ENTRE UN LIT FLUIDISE A HAUTE TEMPERATURE ET UNE SURFACE SOLIDE

Résumé—On considère le transfert thermique d'une surface "mouillée" par un lit fluidisé à haute température. Le rôle variable d'un transfert composant par rayonnement est discuté. On indique les conditions de l'additivité ou de la non-additivité des composantes du transfert et les conditions de l'intervention éventuelle de la composante par rayonnement. On développe des considérations sur le choix d'une température de "délimitation." Des résultats de détermination de l'émissivité effective du lit fluidisé sont discutés.

GESAMTWÄRMEÜBERTRAGUNG ZWISCHEN EINEM HOCHTEMPERATUR GAS-FLIESSBETT UND EINER FESTEN OBERFLÄCHE

Zusammenfassung—Der Wärmeübergang an einer von einem Fliessbett benetzten Oberfläche bei erhöhten Temperaturen wurde untersucht. Die veränderliche Rolle einer Strahlungskomponente für den Übergang wird diskutiert. Die Bedingunge der additiven und nicht additiven Zusammensetzung der Wärmeübergangskomponenten sind angegeben wie auch die Bedingungen für den Austausch der nicht-strahlenden Komponente durch die strahlende. Überlegungen wurden angestellt für die Auswahl der sogenannten "Grenztemperatur". Ergebnisse der Berechnung der effektiven Emissiøvität des Fliessbetts sind diskutiert.

СЛОЖНЫЙ ТЕПЛООБМЕН ПОВЕРХНОСТИ С ПСЕВДООЖИЖЕННЫМ СЛОЕМ

Аннотация—Рассмотрен теплообмен псевдоожиженного слоя с омываемой им поверхностью при высоких температурах и, в частности, обсуждена роль лучистой составляющей обмена, различная в разных условиях. Показаны условия аддитивности и неаддитивности составляющих сложного теплообмена и условия «вытеснения» кондуктивно-конвективной составляющей лучистой. Качественно пояснен эффект так называемого «температурного фактора». Обсуждены результаты определения эффективной степени черноты псевдоожиженного слоя.