HEAT TRANSFER BETWEEN A FLUIDIZED BED AND AN EMBEDDED HIGH-TEMPERATURE SURFACE

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Experimental data on the transfer of heat between a fluidized bed and an embedded high-temperature heat source are considered, as well as the data pertaining to the heat-transfer coefficient as a function of the thermal conductivity of the fluidized gas.

As of the moment, researchers are not unanimous in their opinions as to the causes of the virtually linear (rather than a more pronounced) relationship giving the maximum coefficient of heat transfer between a fluidized bed and a wall as a function of the temperature layer (or wall); relationships of this type are found in most experiments at temperatures below 1000–1100° C [1–5].

In [3], our interest is drawn to the simple illustration based on the "packet model" of a comparatively slight increase in the total heat-transfer coefficient resulting from the appearance of a gradient component under conditions of rather prolonged replacement of particle packets. Under these conditions, the coefficient of heat transfer between the layer and the wall, as is well known, should be regarded most readily as one produced by two series-connected thermal resistances between the wall and the core of the bed—the resistance of the gas interlayer at the wall and the resistance of the packet itself. It is assumed that the radiative exchange has virtually no effect on the thermal resistance of the packet. However, it diminishes the "contact resistance" of the gas interlayer, acting in parallel with conduction and convection. It is obvious that with a slow replacement of the packet, i. e., under conditions in which "contact" resistance does not restrict the over-all transfer of heat, the highest possible value for the coefficient of radiative heat exchange will be incapable of significantly increasing the over-all heat-transfer coefficient.

At the same time there is apparently no need, as was done in [3], for a quantitative evaluation of the components on the basis of a system of relationships of the following type:

$$\alpha = (1 - f_0)/(0.44\,R_t + R_c^{\mathrm{eff}}) + \alpha_r f_0, \qquad (1)$$

$$R_c^{\mathrm{eff}}(1/R_c + \alpha_r)^{-1}. \qquad (2)$$

Malikov [3], presenting relationship (2), in which $a_r = 0.04\varepsilon_{\mathrm{ref}}\, 5.7 \times (T/100)^3$ W/m^2·deg, stipulated correctly that no consideration had been given to the significant difference between the temperature T of the particle surface facing the wall and the core temperature $T_{f.b}$ of the fluidized bed. Consequently, in the general case, rather than in the limit case, the system of equations (1) and (2) is incorrect. Indeed, the coefficient of radiative heat exchange cannot be identical in (1) and (2). In Eq. (2) α_r must be referred to the unknown temperature difference $T_w - T$ so as to be able to calculate it and to sum it with $1/R_c$, since the same temperature difference $T_w - T$ corresponds to the boundaries of the resistance R_c. At the same time, the coefficients α_r in the term $\alpha_r f_0$ must be referred to the temperature difference $T_w - T_{f.b}$ to which the left-hand side of Eq. (1) is referred. Consequently, with substantial values for R_t, the numerical magnitude of the coefficient α_r in Eq. (1) may perhaps be many times smaller than that numerical quantity of the coefficient of radiative heat exchange (to distinguish it, we will refer to it as α_r') which should be substituted into Eq. (2). Let us clarify the initially unexpected circumstance that it is frequently possible to find α_r' rather exactly, even in the case of a pronounced change in the temperature of the particles "visible" to the wall (the packet surface), even when this temperature is not known. It is easy to calculate, for example, that with a reference emissivity of $\varepsilon_{\mathrm{ref}} = 0.8$ for the system and a constant temperature equal to 1000° K for one of the surfaces, the coefficient of radiative heat exchange remains (accurate to within 15%) equal to its limit value (186 W/m^2·deg) regardless of the temperature of the second surface, the temperature of the latter differing from the temperature of the first by as much as 100°. This provides a fundamentally simple means for an approximate computational determination of α_r' for experiments in which $T_w - T_{f.b} < 100°$, requiring no knowledge of the temperature of that row of particles facing the wall (the side of the packet). There is, of course, no possibility here of a direct evaluation of the magnitude of the radiant flux q_r since we still do not know the temperature difference by which α_r' must be multiplied.

In principle, for regimes of slow packet replacement, particularly for a small temperature difference between the bed and the surface, it is possible to estimate the fraction of the radiative exchange by employing expressions such as the corrected system (1)–(2). But for the regimes of intense heat transfer having particular practical interest—characterized by rapid replacement of the packets—this system of equations cannot be recommended for attempts at a quantitative analysis for the reason that these fail to account for the known features of unsteady heat conduction in disperse systems relative to single-component systems; these features which had been indicated in his time by Rubinshteyn [6], and then by Antonishin et al. [7], are particularly significant in the case of brief contact, i. e., under conditions of optimum heat transfer and forced regimes. The existence of a "no-lag" radiative ex-

Table 1

Experimental and Theoretical Values of α_m for the Various Gases Used in the Experiments

Indexes	Gases											
	air $\lambda_{50} = 2.62 \cdot 10^{-2}$ W/m · deg				helium $\lambda_{50} = 15.8 \cdot 10^{-2}$ W/m · deg				carbon dioxide $\lambda_{50} = 1.69 \cdot 10^{-2}$ W/m · deg			
	I	II	III	IY	I	II	III	IV	I	II	III	IV
Material and its density, kg/m^3	2580	2880	2760	3720	2580	2880	2760	3720	2580	2880	2760	3720
Particle dimension, μm	200—250	190—200	100	85—105	200—250	190—200	100	85—105	200—250	190—200	100	85—105
Experimental α_m, W/m^2 · deg	380	420	565	534	1090	1150	1170	1280	283	333	485	406
Theoretical values of α_m from (6) in W/m^2 · deg, and their deviation from experimental data, in %	400	428	542	582	1170	1260	1590	1710	307	332	417	450
	+5.0%	−0.48	−4.1	+9.0	+7.3	+6.5	+36.0	+33.5	+8.5	−3.3	−14.0	+10.8
Theoretical values of α_m from (5), in W/m^2 · deg, and their deviation from experimental data, in %	384	402	538	578	1550	1620	2170	2330	293	306	410	440
	+1.0	−4.3	−4.8	+8.2	+42.0	+41.0	+85.0	+82.0	+3.5	−8.1	−15.5	+8.4

Note: The surface temperature of the heater was taken as the decisive temperature. I) Quartz sand; II and III) glass beads; IV) corundum.

change even further removes the actual mechanism of the heating of the packet from that assumed by Malikov [3] and Baskakov [8].

The role of the radiative flow in the total heat transfer at the instant of contact with the "fresh" packet is particularly significant because the rate of propagation for the radiant energy is many times greater than the rate of propagation for the thermal wave. This role is even greater (and it is this that makes it unique in comparison with a low-temperature bed) at the stage at which the fresh packet approaches the surface, when the gas interlayer between them is thicker and markedly limits the conduction-convection flow without restricting the radiant flow.

The computational (quantitative) evaluations are hindered also by factors such as the actual penetration of radiation into the depths of the packet, as well as the emissivity of the system as a function of the temperature to which the particles and the wall are heated and, finally, the mutual displacement of the particles in the packets.

For forced regimes in which the motion of the packet is so rapid that there is no significant rise in particle temperature, consideration of R_t and the concepts of both the total α and the heat-transfer coefficient are not applicable, and judgments as to the magnitude of the attained α_t and their decomposition into components must be built on the idea that such regimes are attained in ordinary high-temperature fluidized beds when the bed exhibits high effective porosity, i. e., on passing $\alpha_{c\text{-}c\ \max}$. Therefore

$$\alpha_{t.f} < \alpha_r + \alpha_{c\text{-}c\ \max} \tag{3}$$

The experimentally derived flat maxima for the coefficient of heat transfer for the wall are flatter in the case of high-temperature heat transfer than in the case of low-temperature heat transfer and this confirms the intensification of the role played by radiative exchange as the rate of filtration increases when $\alpha_{c\text{-}c}$ diminishes.

It was demonstrated in [4] that the following inequality is valid:

$$\alpha_{t.m} < \alpha_{c\text{-}c\ \max} + \alpha_{r.m} \tag{4}$$

Of course, inequalities (3) and (4) pertain to the values averaged in time and over the heat-transfer surfaces, rather than to the instantaneous local values.

It follows from inequality (4) that when $\alpha_{c\text{-}c\ \max}$ (even if calculated with comparative accuracy from some empirical interpolational formula rather than according to a theoretical formula) is eliminated from the experimentally derived $\alpha_{t.m}$ for high-temperature transfer, it is not the actual but the understated values of $\alpha_{r.m}$ that we obtain. This difference will be even smaller than α_r under the conditions of $\alpha_{t.m}$, since $\alpha_{c\text{-}c\ \max}$ is not achieved under these conditions.

Nevertheless, this difference—or in a more generalized form (see below), the deviation of the nature of the change in α_m for a "low-temperature" relationship with λ_g—may be of some practical interest in calculating the "correction for radiation" which must be introduced into the theoretical $\alpha_{c\text{-}c\ \max}$ to obtain $\alpha_{t.m}$ for high-temperature heat transfer (here and throughout we will employ the term "high-temperature heat transfer" to encompass both the case of heat transfer between a high-temperature bed and a "cold" surface as well as the case of the heat transfer between a high-temperature surface and the bed cooling that surface, with that bed possibly exhibiting an extremely low temperature).

Table 2

Composition and Thermal Conductivity λ_g for Gases Used in the Jakob and Osberg [11] Experiments

No.	Gas	λ_g at 0° C, $W \cdot m^{-1} \cdot deg^{-1}$
1	H_2	0.1748
2	He	0.1470
3	81% H_2+19% N_2	0.1244
4	78.9% H_2+21.1% N_2	0.1097
5	33.3% H_2+66.7% N_2	0.0471
6	air	0.0244
7	CO_2	0.0147
8	Freon-12	0.00827

Of course, the difference $\alpha_{t.m} - \alpha_{c\text{-}c\ \max}$ and the correction factor will also be functions of the selected temperature determining the physical constants in the calculation of $\alpha_{c\text{-}c\ \max}$. For the time being, in the interest of simplicity, we will assume the temperature of the heating surface as the one that is decisive for the system.

Since the existing interpolational formulas proposed in [9] and [10] are simple and rather convenient for the calculation of $\alpha_{c\text{-}c\ \max}$, and since these have not been verified, up to the present time, over a wide range of variations in λ_g because of a lack of appropriate experimental data in the literature, we carried out special measurements of $\alpha_{c\text{-}c\ \max}$ under low-temperature conditions ($t_w = 50°$, $t_{f.b} < 50$), i. e., for negligibly small α_r, in beds fluidized not only by air, but also with helium and CO_2. Under these conditions the correction factor accounting for the fact that the coefficient for the formula from [9] depends on Pr would be negligibly small and the numerical value of 0.86 pertains to the diatomic gases.

For better confirmation of the results in connection with the effect of the properties of the gas, we measured the heat-transfer coefficients with the identical sensor (7 mm in diameter and 43 mm in height) in the same column (37 mm in diameter). In all of the experiments the sensor was positioned identically—along the axis of the column, at a distance (clearance) of 20 mm from the gas-distribution grid. A porolon layer (10 mm) and a net with a mesh of 100 μm served as the gas-distribution grid. Beneath the grid there was another layer of slag balls 0.5–1 mm in diameter, and this bed was 25 mm high. The experimental results, as well as those from calculations according to the formulas from [9] and [10], are given in Table 1.

We see from Table 1 that the formula from [9]

$$Nu_m = 0.86\,Ar^{0.2} \tag{5}$$

Table 3

Relative Data at the Jakob and Osberg [11]

	d, μm			
	31	61	153	292
$\frac{\alpha_1}{\alpha_6}$*; $\left(\frac{\lambda_1}{\lambda_6}\right)^{0.6}$; δ, %	2.46; 3.26; +32.2	2.66; 3.26; +22.3	2.99; 3.26; + 9.0	3.36; 3.26; − 3.0
$\frac{\alpha_2}{\alpha_6}$; $\left(\frac{\lambda_2}{\lambda_6}\right)^{0.6}$; δ, %	2.08; 2.94; +41.2	2.51; 2.94; +17.0	2.80; 2.94; 5.0	3.07; 2.94; − 4.3
$\frac{\alpha_3}{\alpha_6}$; $\left(\frac{\lambda_3}{\lambda_6}\right)^{0.6}$; δ, %	2.18; 2.66; +22.0	2.43; 2.66; + 9.3	2.90; 2.66; − 8.3	3.10; 2.66; −14.3
$\frac{\alpha_4}{\alpha_6}$; $\left(\frac{\lambda_4}{\lambda_6}\right)^{0.6}$; δ, %	2.05; 2.46; +20.0	2.40; 2.46; + 2.2	2.68; 2.46; − 8.3	3.00; 2.46; −18.0
$\frac{\alpha_5}{\alpha_6}$; $\left(\frac{\lambda_5}{\lambda_6}\right)^{0.6}$; δ, %	1.44; 1.48; + 2.7	1.50; 1.48; − 1.8	1.66; 1.48; −11.0	1.79; 1.48; −17.4
$\frac{\alpha_7}{\alpha_6}$; $\left(\frac{\lambda_7}{\lambda_6}\right)^{0.6}$; δ, %	0.731; 0.738; +0.8	0.773; 0.738; − 4.5	0.792; 0.738; −7.0	0.700; 0.738; + 5.3
$\frac{\alpha_8}{\alpha_6}$; $\left(\frac{\lambda_8}{\lambda_6}\right)^{0.6}$; δ, %	0.536; 0.522; −2.8	0.550; 0.522; − 5.2	0.518; 0.522; +0.5	0.487; 0.522; + 7.0

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*The subscripts correspond to the sequential numbers of the gases in Table 2.

is not confirmed on fluidization with helium with all the investigated layers, while the formula from [10]

$$\alpha_{\text{c-c max}} = 35.7\rho^{0.2}\lambda_g^{0.6}d^{-0.36} \quad (6)$$

describes rather well the experimental data, with the exception of the transfer of heat by the beds made up of the very finest of particles (d ≪ 100 μm) fluidized with helium. Even with (6), for these we obtain values of $\alpha_{\text{c-c max}}$ exaggerated relative to the experimental values by more than 30%. This divergence can be explained only in part by the "contamination" of the helium by water vapor on passage of the former through the flow meter—a wet gas meter. Apparently, for particles smaller than 100 μm the forces of molecular attraction lead to the formation of clumps, and it is the characteristics of the clumps rather than of the particles that must be substituted into the formulas. In other words, the porosity and thermal resistance of the packets are sharply increased.

We will undertake an additional evaluation of the suitability of formula (6) on the basis of the relative data of Jakob and Osberg [11], measuring the transfer of heat from thin wires (ϕ = 0.13 mm) by beds fluidized with various gases exhibiting thermal conductivities λ_g varying from 0.0083 (Freon-12) to 0.1748 $W \cdot m^{-1} \cdot deg^{-1}$ (hydrogen) (see Table 2); as is well known, the absolute values of the heat-transfer coefficients derived in [11] are inconvenient for comparison with the data of other researchers because of the great effect of the geometric factor. Table 3 therefore shows only the ratios between the experimental heat-transfer coefficients in the case of fluidization by various gases and mixtures of gases (α_i) and the heat-transfer coefficients derived under identical conditions, but for fluidization with air (α_a).

Table 3 also shows the $(\lambda_i/\lambda_a)^{0.6}$ ratios for these same cases and, finally, δ is the deviation of $(\lambda_i/\lambda_a)^{0.6}$ from α_i/α_a, expressed in percent and showing the extent to which the experimental relationship between α and the thermal conductivity of the gas deviates from agreement with formula (6). As we can see from Table 3, the deviation of the relative data after Jakob and Osberg from formula (6) does not exceed 18% for particles larger than 61 μm, while for particles 61 μm in size it amounts only to 22.3% for more "remote" extrapolations (from air to helium and hydrogen). Thus for particles on the order of 100 μm and larger, formula (6) is also in satisfactory agreement with the results derived by Jakob and Osberg.

It is advisable at this point to beware of a simple calculation of α_m according to formula (6) (without consideration of a special correction factor for the convection component) for the fluidized beds under high pressure. Under conditions of a high gas pressure, because of the markedly increasing volumetric specific heat of the medium, there is a pronounced increase in the role of the filtration mixing of the medium at the heat-transfer surface [14].

If we now use formula (6) to calculate the transfer of heat in fluidized beds consisting of particles ranging in diameter from 100 μm to 1.5 mm, and if we take the temperature of the heat-transfer surface as the theoretical temperature for the high-temperature bed, on the basis of the experiments that have been carried out, the correction factor (the correction factor for high-temperature heat transfer) can be evaluated as shown below.

For the temperatures prevailing in the experiments, we find the λ of the air and calculate $(\lambda/\lambda_1)^{0.6}$, where λ_1 is the thermal conductivity of the air for the least decisive temperature for which the total maximum heat-transfer coefficient $\alpha_{1\,m}$ was measured in experiments with the given material. At temperatures of t_1 = 115–160° C (see Table 4) the radiative component of the exchange was clearly negligible. Then, from the experimental values of $\alpha_{1\,m}$ we calculate the α extrapolated to the higher temperatures, multiplying α_{1m} by $(\lambda/\lambda_1)^{0.6}$, and we find the ratios of the maximum experimental values of the heat-transfer coefficients to α_{ex} (see Table 4). It is these ratios that are the values of the correction factor K_{ht} by which $\alpha_{\text{c-c max}}$ from (6) must be multiplied in order to account for features of high-temperature heat transfer. The values of $\alpha_{exp.t}/\alpha_{ex}$, somewhat smaller than unity and varying irregularly, were obtained primarily for small particles and are obviously associated with the fact that the K_{ht} for them is equal to unity within the error limits of the experiment.

The calculated $K_{ht} = \alpha_{exp.t}/\alpha_{ex}$ (see Table 4) in first approximation can be described by the interpolational formula

$$K_{ht} = 1 + \frac{10^4 d - 2.5}{11.7}\,(0.296t^{0.22} - 1) \quad (7)$$

for d from $2.5 \cdot 10^{-4}$ to $14.2 \cdot 10^{-4}$ m and t from 250 to 950° C.

In the derivation of formula (7) it was assumed that for the theoretical temperatures of the system $t = t_w < 250$ °C, $K_{ht} = 1$; it is also equal to unity (i.e., it was not necessary to introduce the correction factor for all temperatures) if the particles were less than 250 μm in diameter.

The structure of (7) is such that the substitution of temperatures below 250° C and diameters less than 250 μm is devoid of significance.

Formula (7) corresponds to our experimental data, with a deviation not exceeding 10.5%, and to the data for the larger particles (d = 1.42 mm) where the correction factor K_{ht} is most significant, with an error not greater than 3.35%.

The interpolational formula (7) can be refined, its structure improved, and its limits of application expanded only after the accumulation of new data from systematic measurements of $\alpha_{exp.t}$ in high-temperature beds over a wide range of temperatures. It would be desirable to carry out these measurements over the entire range under identical equipment conditions and with the same materials, so that the comparison of the data would not be clouded by the virtually uninvestigated, but doubtlessly important effect of differences in the porosities of various beds in the case of minimum fluidization [4]. This porosity m_0 reflects the porosity of the aggregate ("packets") of particles

Table 4

Experimental Data and Correction Factor K_{ht}

Material	ρ, kg/m^3	d · 10^6 m	t_w, °C	$\lambda_g \cdot 10^2$, W/m · deg	$\alpha_{exp.t}/\alpha_{ex}$	K_{ht}	Deviation, %
Quartz sand	2580	1420	135	3,29	1	—	—
			280	4.22	1.087	—	—
			375	4.76	1.070	1,060	−0.94
			525	5.46	1,103	1,140	+3.35
			640	6.05	1,168	1,195	+1.61
			790	6.66	1,222	1,251	+2.37
			925	7.27	1,333	1,301	−2.40
The same	2640	630	115	3.20	1	—	—
			215	3.78	0.945	—	—
			315	4.36	1,005	1.013	+0,8
			455	5.12	0,965	1.042	+7.98
			555	5.61	1.060	1.058	−0.2
			685	6.18	1,032	1.066	+3.29
			780	6.60	1,100	1.088	−1.09
			905	7.15	1.122	1.101	−1.87
The same*	2640	630	115	3,20	1	—	—
			385	4.76	0.961	1,022	+6.33
			550	5.58	1.025	1.050	+2,44
			765	6.50	1.058	1.076	+1.70
			950	7.40	1.098	1.098	0
The same	2640	280	145	3.40	1	—	—
			210	3.78	0.958	—	—
			360	4.60	0,958	1,002	+4.59
			520	5.46	0,940	1.004	+6.80
			655	6.05	0,983	1,005	+2.24
			925	7.27	1,005	1,008	+0,30
Electrocorundum	3720	95	160	3.45	1	—	—
			445	5.13	0,930	1	+7. 53
			530	5.53	0.905	1	+10.50
			600	5,81	0.948	1	+5.48
			760	6.50	0.930	1	+7.53
			850	6.92	9.925	1	+8.10

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*Experiments with shifted spiral.

in a nonuniform fluidized bed (if not equal to the latter), and it is natural to expect that the more "porous" packets will exhibit greater thermal resistance.

The porosity of the packets is a function of the shape, dimension, and state of the surface formed by the particles. In general, it is the greater, the more rigorously the material is monodisperse and the greater the ratio of the surface forces (friction, adhesion) to the mass forces, i. e., all other conditions being equal, the porosity increases with transition from smooth to rough particles, from heavy to light materials, from large to fine particles, or from spherical to laminar shape.

We note that for a monofraction material a denser packing is achieved, in principle, for smooth multifaceted particles, rather than for those which are spherical.

One of the several fractions of quartz sand in our experiments (a fraction of 400–1000 μm with an average diameter of 630 μm) differed "anomalously" because of the low porosity of the dense bed ($m_0 = 0.365$, while the porosity of the remaining fractions was 0.39–0.413) while it exhibited higher $\alpha_{\mathrm{exp.t}}$ than is usual for quartz sand of similar average diameter.

Considerably smaller α_m than should have been expected on the basis of the bulk weight of the particles were obtained in the Kharchenko and Makhorin experiments [1] for fluidized chamotte beds, and this was apparently also a result of the fact that the particles attained the high mobility characteristic for the heat-transfer maximum only for an elevated effective bed porosity [4] or, in the concepts of "packet theory," on attainment of high "packet" porosity. The elevated porosity (low thermal conductivity) of the actual chamotte particles must play some role here, but it is apparently one that is secondary.

The bulk density of the material is associated with some inverse relationship not only with the porosity of the dense layer [bed], but also with the porosity of the packets, and it seems natural to attempt to introduce into the interpolational formula for α_m a quantity ρ_{bulk} or m_0 to account for the differences in the packet porosities. However, for the time being, this cannot be done satisfactorily on the basis of literature data on ρ_{bulk} and m_0 because of nonstandardization and differences in the methods for the determination of ρ_{bulk} used by various authors. Thus, for example, taking the ρ_m and ρ_{bulk} for sand and chamotte from the Kharchenko data [12], we should expect to introduce $m_0^{-1.7}$ into the interpolational formula (6) and to assume $m_0 = 0.43$ as the "base" porosity for which no correction factor is needed (it is equal to unity). According to the familiar data of Baerg, Klassen, and Gishler [13], however, the transfer of heat from layers exhibiting $m_0 = 0.6$ (alumina) and even $m_0 = 0.69$ (iron powder) are well "covered" by formula (6) without correction factors [10].

NOTATION

d is the particle dimension; f_0 is the fraction of time during which the heat-transfer surface is flushed by the gas bubble; K_{ht} is a correction factor; m_0 is the porosity of the fluidized bed for minimum fluidization; R_c is the contact resistance; R_t is the thermal resistance of the packet; T, $T_{f.b}$, and T_w are the absolute temperatures, respectively, of the side of the packet facing the heat-transfer surface, of the core of the bed, and of the heating surface; α is the coefficient of heat transfer between the surface and the fluidized bed; α'_r and α_r are the coefficients of radiative heat exchange between the surface and the fluidized bed, referred, respectively, to the temperature differences $T_w - T$ and $T_w - T_{f.b}$; $\alpha_{t.m}$, $\alpha_{c\text{-}c\ \max}$, $\alpha_{\mathrm{exp.t}}$, $\alpha_{t.f}$, and α_{ex} are, respectively, the total maximum, the maximum conductive-convective, the experimental total, the total in a forced regime, and the total heat-transfer coefficient extrapolated to higher temperatures; λ_g, λ_a, λ_i, and λ_1 are, respectively, the thermal conductivities for the gas, the air, and the i-th gas from those indicated in Table 2 and for the air at a temperature t_1; ρ_m and ρ_{bulk} are the densities of the material of the particles and the bulk density of the bed.

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