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SIMILARITY OF TRANSFER PROCESSES IN DISPERSE SYSTEMS WITH SUSPENDED PARTICLES

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Based on allowance for special features of the hydrodynamics of disperse systems with suspended particles within the framework of dimensional theory the author obtained a complete system of dimensionless groups (5) that describes the similarity of transfer processes. It includes the new numbers Fr_t^* and J_s^* that contain the excess velocity of gas $u - u_t^*$ and are important generalized characteristics of convective particle motion. Characteristic examples of using system (5) for generalization of experimental data are given.

The study of transfer processes on small laboratory setups at room temperature and pressure is one of the most important stages of designing large-scale industrial apparatuses. In this connection, the problem of a scale transition that consists of developing the rules of extending (converting) the results of laboratory experiments to a real apparatus is pressing. Its solution is based on analysis of the similarity of transfer processes in a dispersion medium and construction of a system of a minimum of dimensionless similarity numbers that are composed of independent characteristics of a concrete system and enable us to unambiguously determine the parameters of a laboratory setup which models the industrial apparatus.

In the present work, the indicated problem is solved as applied to a rather wide class of disperse systems with suspended particles: a fluidized bed, a circulating fluidized bed, and vertical pneumatic transport. The possibility of integrating them into one class is based on the existence of an important common property. In these systems, the particle weight is compensated by the force of gas friction and the entire excess power of the fan $\Delta p(u - u_t^*)$ is expended on accelerating suspended particles and producing a complex pattern of their convective (circulation) motion:

a) one or several contours of the internal circulation of the particles (up – in the trails of gas bubbles, down – in the remaining emulsion phase) in a fluidized bed;

b) one internal circulation contour (up – in the core of the layer, down – in the annular zone near standpipe walls) in a circulating fluidized bed;

c) the upward convective motion of the particles over the entire cross section of the standpipe in their vertical pneumatic transport.

The intensity of large-scale motions of a solid phase is, apparently, governed by the excess rate of gas filtration $u - u_t^*$. As will be shown below, this quantity is of primary importance in the development of the rules of a scale transition for disperse systems with suspended particles.

The problem of scaling in disperse systems has attracted researchers' attention for a long time, and there is a number of attempts to solve it in the literature. As a rule, the sought system of dimensionless similarity numbers resulted from one or another variant of making the equations of balance of masses and momenta of phases dimensionless.

The basic known systems of similarity numbers [1-8] are summed up in Table 1. Analysis of the given results permits the following conclusions:

1. The number of dimensionless groups that describe the similarity of dispersed beds is 4-5. This yields the corresponding number of independent equations for determination of the parameters of a cold laboratory stand.

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TABLE 1. Similarity Numbers for Disperse Systems with Suspended Particles

Fluidized bed	Circulating fluidized bed	Vertical pneumatic transport
$\frac{\rho_s-\rho_f}{\rho_f}, \frac{u_{mf}^2}{gd}, \frac{u_{mf}d\rho_f}{\mu_f}, \frac{H}{D}$, [1]	$\frac{u^2}{gD}, \frac{\rho_s}{\rho_f}, \frac{d}{D}, \frac{ud\rho_f}{\mu_f}, \frac{J_s}{\rho_s u}$, [4]	$\frac{J_s}{\rho_f u}, \frac{uD\rho_f}{\mu_f}, \frac{D}{d}, \frac{cs}{c_f}$*)
$\frac{Lg}{u^2}, \frac{L}{d}, \frac{\rho_s}{\rho_f}, \frac{ud\rho_f}{\mu_f}$, [2]	$\frac{u^2}{gd\theta}, \frac{\rho_s}{\rho_f}, \frac{D}{d\theta}$, Ar, $\frac{J_s}{\rho_s u}$ [5]	
$\frac{D}{d}, \frac{L}{d}, \frac{\rho_f}{\rho_s}, \frac{u^2}{gd}$, Ar, [3]	$\frac{u^2}{gD}, \frac{\rho_s}{\rho_f}, \frac{u}{u_t}, \frac{J_s}{\rho_s u}$, [6]	
	$\frac{u^2}{gD}, \frac{\rho_s}{\rho_f}, \frac{u}{u_{mf}}, \frac{J_s}{\rho_s u}$, [7]	

*)The system is composed of the numbers used by different authors in generalization of the experimental data of [8].

Clearly this number of equations is inadequate to find seven sought parameters: J_s (or H_{mf}), u, d, D, H, ρ_s, and c_s.

2. The systems of similarity numbers are narrowly specialized, i.e., are constructed as applied to a concrete disperse system.

3. Some of the complexes are formed purely formally without allowance for special properties of disperse systems with suspended particles and have no clear physical meaning, which makes one hold their correctness in doubt: u^2/gD, u^2/gd, u/u_{mf}, u/u_t, and $J_s/\rho_s u$.

No strong evidence of the advantage of one or another system of similarity numbers has been found in the literature.

The present work seeks to obtain a universal, complete system of dimensionless similarity numbers that allow for specific properties of the disperse systems in question and make it possible to unambiguously determine all the parameters of a laboratory stand which models the real apparatus.

Based on the above specific features of the hydrodynamics of disperse systems with suspended particles we can recognize two basic classes of transfer processes that are characterized by significantly different velocity and length scales:

1) Macroprocesses due to the circulation motion of particles. The characteristic scales of these processes are: $u - u_t^*$, D, and H. The controlling system of independent parameters has the form:

$$\begin{Bmatrix} J_s \\ H_{mf} \end{Bmatrix}, \quad u - u_t^* , D , H , h , g , \rho_s , c_s , \tag{1}$$

where J_s and H_{mf} reflect the mass of dispersed material in the bed and naturally are mutually exclusive. The quantity H_{mf} is used in the case of a fluidized bed and a circulating fluidized bed that operates according to a "furnace" scheme when the weight of dispersed material in the lifting standpipe is prescribed; J_s is included in system (1) in the case of vertical pneumatic transport and a circulating fluidized bed that operates according to a "chemical reactor" scheme when the circulation particle flux is controlled.

2) Microprocesses associated with gas-particle interphase interaction. The characteristic scales are: u_t^* and d. The system of dimensional controlling parameters has the form:

$$u_t^* , d , g , \rho_f , \rho_s , \mu_f , D_f , \lambda_f , c_f , c_s . \tag{2}$$

We note that, for description of "boundary" processes – the interaction of a two-phase medium with stationary elements of the setup – we need to introduce the rate of gas filtration u in addition to systems (1) and (2).

The arbitrary characteristic of the disperse system in the general case will be a function of the following parameters:

TABLE 2. Modeling of a Furnace and a Fluidized-Bed Gas Producer That Operate According to "Chemical Reactor" and "Furnace" Schemes

Quantity	Furnace, $T=800^{\circ}$C, $p=0.1$ MPa	Laboratory setup	Gas producer, $T=1000^{\circ}$C, $p=2$ MPa	Laboratory setup
		"Chemical reactor"		
J_s, kg/(m^2·sec)	50.0	83.2	50.0	15.8
H, m	12.0	2.2	12.0	19.1
D, m	1.0	0.18	1.0	1.59
u, m/sec	6.0	2.57	6.0	7.6
d, m	$0.2 \cdot 10^{-3}$	$0.048 \cdot 10^{-3}$	$0.2 \cdot 10^{-3}$	$0.31 \cdot 10^{-3}$
ρ_s, kg/m^3	2600	10,064	2600	650
c_s, J/(kg·°C)	730	660	730	610
		"Furnace"		
H_{mf}, m	0.5	0.092	0.5	0.8
H, m	12.0	2.2	12.0	19.2
D, m	1.0	0.18	1.0	1.59
u, m/sec	6.0	2.57	6.0	7.6
d, m	$0.2 \cdot 10^{-3}$	$0.048 \cdot 10^{-3}$	$0.2 \cdot 10^{-3}$	$0.31 \cdot 10^{-3}$
ρ_s, kg/m^3	2600	10,064	2600	650
c_s, J/(kg·°C)	730	660	730	610
ρ_f, kg/m^3	0.31	1.2	4.81	1.2
μ_f, kg/(m·sec)	$449 \cdot 10^{-7}$	$179 \cdot 10^{-7}$	$365 \cdot 10^{-7}$	$179 \cdot 10^{-7}$
u_f, m/sec	1.06	0.45	0.81	1.03

$$\begin{Bmatrix} J_s \\ H_{mf} \end{Bmatrix}, \quad u - u_t^*, D, H, h, g, \rho_f, \rho_s, c_f, c_s, u_t^*, d, \mu_f, D_f, \lambda_f, u. \tag{3}$$

The rate u_t^* is unambigously determined by ρ_f, ρ_s, ε, d, μ_f, and g, and we can eliminate it from (3). By using a π-theorem of dimensional theory we obtain the system of dimensionless groups:

$$\begin{Bmatrix} \bar{J}_s^* \\ H_{mf}/H \end{Bmatrix}, \mathrm{Fr}_t^*, \mathrm{Ga}, \mathrm{Re}, \mathrm{Pr}, \mathrm{Sc}, \frac{h}{H}, \frac{H}{D}, \frac{c_s}{c_f}, \frac{\rho_s}{\rho_f}, \frac{d}{D}. \tag{4}$$

The simplex d/D that is the ratio of micro- and macroscales of length can be eliminated from system (4) as being formal and physically meaningless. The number Ga is replaced by a more frequently used number Ar. System (4) will take the form:

$$\begin{Bmatrix} \bar{J}_s^* \\ H_{mf}/H \end{Bmatrix}, \mathrm{Fr}_t^*, \mathrm{Ar}, \mathrm{Re}, \mathrm{Pr}, \mathrm{Sc}, \frac{h}{H}, \frac{H}{D}, \frac{c_s}{c_f}, \frac{\rho_s}{\rho_f}. \tag{4a}$$

The system obtained characterizes the total similarity of local processes. The total similarity of integral processes (the dispersed beds themselves) is obtained for the corresponding equality of the dimensionless parameters:

$$\begin{Bmatrix} \bar{J}_s^* \\ H_{mf}/H \end{Bmatrix}, \mathrm{Fr}_t^*, \mathrm{Ar}, \mathrm{Re}, \mathrm{Pr}, \mathrm{Sc}, \frac{H}{D}, \frac{c_s}{c_f}, \frac{\rho_s}{\rho_f}. \tag{5}$$

The seven complexes from system (5)

$$\begin{Bmatrix} \bar{J}_s^* \\ H_{mf}/H \end{Bmatrix}, \mathrm{Fr}_t^*, \mathrm{Ar}, \mathrm{Re}, \frac{H}{D}, \frac{c_s}{c_f}, \frac{\rho_s}{\rho_f} \tag{6}$$

yield seven independent equations for determination of the parameters of a cold laboratory stand that models the industrial apparatus:

$$\begin{Bmatrix} J_s \\ H_{mf} \end{Bmatrix}, d, D, H, u, \rho_s, c_s. \tag{7}$$

Table 2 presents the results of calculating based on (6) parameters (7) of the laboratory circulating fluidized beds ($T = 20^\circ$C, $p = 0.1$ MPa, the fluidizing agent is air) that model conductive-convective processes of transfer in high-temperature setups which operate according to different schemes of control over the amount of dispersed material in the lifting standpipe.

Since system (6) enables us to determine all the parameters of the laboratory stand it is complete in this regard. One of its main features is introducing the new numbers Fr_t^* and $\bar{J}_s^*$ based on the excess gas velocity $\bar{u} - u_t^*$ and abandoning completely the physically meaningless complexes. It can easily be seen that Fr_t^* and $\bar{J}_s^*$ are generalized characteristics of convective, large-scale particle motion. The numbers Fr_t^* and $\bar{J}_s^*$ have the following physical meaning: Fr_t^* is the relation of the average kinetic energy of the particles to their potential energy; $\bar{J}_s^*$ is the concentration of the particles in the system (or in its individual zones). We note that the Ar number serves as the characteristic of small-scale transfer processes which govern the interphase interaction. As will be shown these complexes will play an important part when the problem of scaling the apparatuses with disperse systems is solved and make it possible to obtain rather simple generalized dependences for calculation of different characteristics of dispersed beds.

Experience of successful use of the numbers of system (5) for a wide generalization of experimental data has been accumulated in the literature. We note some characteristic results.

Fluidized bed. For calculation of the diameter of a gas bubble, a simple dependence

$$\frac{D_b}{h} = 1.3\,\mathrm{Fr}^{1/3}\left(\frac{h}{H}\right)^{-1/3} = 1.3\,\mathrm{Fr}_h^{1/3}, \tag{8}$$

that generalizes practically all the experimental data available in the literature (more than 20 works) was obtained in [9]. The region for checking (8) is: $0.1 \le D \le 1.8$ m; $10^{-4} \le \mathrm{Fr}_h \le 2\cdot 10^{-1}$.

It is proposed to calculate the concentration of particles in the bed by the formula [10]

$$\frac{\varepsilon - \varepsilon_{mf}}{1 - \varepsilon} = \frac{H - H_{mf}}{H_{mf}} = 0.7\,\mathrm{Fr}^{1/3}\left(\frac{H}{D}\right)^{1/2}, \quad (1 \le H_{mf}/D \le 4;\ 0.1 \le D \le 1.8\ \mathrm{m}). \tag{9}$$

For calculation of the concentration of particles in the superbed zone, the relation

$$\frac{1 - \varepsilon_{fb}}{1 - \varepsilon} = \exp\left(-1.2\left(\frac{h}{H_{mf}} - 1\right)\mathrm{Fr}^{-1/3}\right) \quad (0.13 \le d \le 0.25\ \mathrm{mm}) \tag{10}$$

is obtained in [11].

In [12], the semiempirical equation

$$\mathrm{Nu}_{c-c} = 0.74\,\mathrm{Ar}^{0.1}(1 - \varepsilon)^{2/3}\left(\frac{c_s}{c_f}\right)^{0.24}\left(\frac{\rho_s}{\rho_f}\right)^{0.14} + 0.046\,\frac{\mathrm{Re}}{\varepsilon}\,\mathrm{Pr}\,(1 - \varepsilon)^{2/3}, \tag{11}$$

where ε is yielded by (9), is proposed based on the analysis of numerous experimental data on conductive-convective heat transfer of a bed with an immersed surface. Dependence (11) is checked in a wide range of variation of experimental conditions: $1.4 \cdot 10^2 \le \mathrm{Ar} \le 1.1 \cdot 10^7$, $0.1 \le p \le 10.0$ MPa. This makes it one of the most universal formulas known in the literature.

In generalization of the experiments on local mass transfer throughout the height of a vertical cylinder [13] when there appears a new independent parameter – the cylinder height l – it is convenient to introduce a mass-transfer variant of the Froude number $\mathrm{Fr}_l = u^2/gl$ instead of Re. With the use of this quantity we obtained a compact formula that describes the data of [13]:

$$\mathrm{Sh} = 1.5\,(\mathrm{Fr}_l/\varepsilon_\mathrm{p})^{0.56}\,(l/x)^{0.29}\,, \quad (0.12 \le d \le 0.32 \ \ \mathrm{mm})\,. \tag{12}$$

In a similar generalization of the experimental data [14] on the average mass transfer of a 10 mm thick vertical plate, two equivalent formulas

$$\langle \mathrm{Sh} \rangle = 0.3\,\mathrm{Ar}^{0.35}\,\mathrm{Fr}_l^{0.15} \left(\frac{l}{d}\right)^{-0.35}, \tag{13}$$

$$\langle \mathrm{Sh} \rangle = 1.0\,\mathrm{Ar}^{0.2}\,\mathrm{Re}^{0.3} \left(\frac{l}{d}\right)^{-0.5} \quad (0.32 \le d \le 2.5 \ \ \mathrm{mm}) \tag{14}$$

are established.

Using the Fr number (or its local analog Fr_h), we also obtained a rather simple formula that generalizes systematic experimental data [15] on the force which acts on a horizontal disk immersed in a fluidized bed:

$$\frac{F}{\rho_\mathrm{s}\, g d_1^3} = 0.3\,\mathrm{Ar}^{-0.17}\,\mathrm{Fr}_h^{0.5} \left(\frac{h}{d_1}\right)^{1.5} \quad (0.02 \le D_\mathrm{t} \le 0.08 \ \ \mathrm{m}\,;\ H_\mathrm{mf} \ge 0.5 \ \ \mathrm{m}\,; \quad 0.074 \le d \le 0.695 \ \ \mathrm{mm})\,. \tag{15}$$

We note that, to generalize their data, the authors of [15] used a Froude number $\mathrm{Fr}_d = (u - u_\mathrm{mf})^2/gd$ formed from characteristics of large-scale $(u - u_\mathrm{mf})$ and small-scale (d) transfer processes. For this reason, this number is physically meaningless.

Circulating fluidized bed. As is known, this disperse system has properties of both a fluidized bed (in the lower part) and pneumatic transport (in the upper, transport zone). In the case when an independent parameter is H_mf, i.e., the bed operates according to the "furnace" scheme, we found

$$1 - \varepsilon = \frac{\rho}{\rho_\mathrm{s}} = 0.053\,\mathrm{Fr}_\mathrm{t}^{0.62} \left(\frac{h}{H}\right)^{-0.45} \tag{16}$$

to calculate the density distribution along the height of the transport zone of a 12 MW boiler [16].

In the experiments analyzed, H_mf was maintained constant and therefore was not processed. For beds that operate according to the "chemical reactor" scheme when J_s is an independent, input parameter, a simple equation

$$1 - \varepsilon = \bar{J}_\mathrm{s} \left(\frac{h}{H}\right)^{-0.82}, \tag{17}$$

that generalizes a considerable body of experimental data (10 works) was obtained.

For calculation of the conductive-convective component of the heat-transfer coefficient, the equation, in view of (17), has the form

$$\mathrm{Nu}_{c\text{-}c} = 1.65\,\mathrm{Ar}^{0.19}\,\bar{J}_s^{0.5}\left(\frac{h}{H}\right)^{-0.41} + 0.00049\mathrm{Ar}^{0.69}\,\mathrm{Pr}\,. \tag{18}$$

The formula is checked under the conditions: $0.1 \le p \le 5.0$ MPa; $0.58 \le d \le 0.827$ mm; $1 - \varepsilon \le 0.2$. Because of the features of the hydrodynamics of the bed near the standpipe walls (the descending motion of particles and gas filtration with a rate that is substantially lower than the average gas velocity) the number Ar entered in the convective component $\mathrm{Nu}_{c\text{-}c}$ instead of the number Re.

Vertical pneumatic transport. For calculation of the tangential stresses on the standpipe wall, a simple formula

$$\frac{\tau}{\rho_f u^2} = 0.17\bar{J}_s^{0.5}\,, \tag{19}$$

that holds true within $5\cdot 10^{-4} \le \bar{J}_s \le 2\cdot 10^{-2}$ was obtained in [18].

Taking into account that the velocity of particle motion is determined by the relation [19] $v = (u - u_t^*)/\varepsilon$, from the expression for the density of the circulating flow $J_s = \rho v$ we have the relationship between the concentration of the particles and the number $\bar{J}_s^*$

$$1 - \varepsilon = \bar{J}_s^*/(1 + \bar{J}_s^*)\,. \tag{20}$$

Formula (20) in the general case is a transcendental equation for ε (since ε appears in the expression for u_t^*). In the case of rarefied systems ($\bar{J}_s^* \le 0.01$), $1 - \varepsilon \approx \bar{J}_s^* - \bar{J}_s$.

To calculate $\alpha_{c\text{-}c}$, a dependence similar to (11) and (18) was obtained in [20]:

$$\mathrm{Nu}_{c\text{-}c} = 54.0\mathrm{Ar}^{0.17}\,\bar{J}_s + 0.021\mathrm{Re}^{0.8}\left(\frac{d}{D}\right)^{0.2}\mathrm{Pr}^{0.43}\,. \tag{21}$$

The region for checking (21) is: $\bar{J}_s \le 10^{-2}$; $0.076 \le d \le 0.15$ mm; $12 \le u \le 42$ m/sec.

Conclusions. Based on the analysis of special features of the hydrodynamics of dispersed beds with suspended particles within the framework of dimensional theory we obtained a complete system of dimensionless groups (5) that describes the similarity of transfer processes in the media indicated. The system of complexes (6) enables us to find all the parameters of the cold laboratory stand that models the industrial apparatus and thus determine the sought rules of a scale transition. The complex Fr_t^* and $\bar{J}_s^*$ introduced based on the excess gas velocity $u - u_t^*$ are important generalized characteristics of the convective (circulation) motion of the particles in these dispersion media. The calculated correlations obtained using these numbers are quite simple and have, as a rule, a large degree of universality. This makes them very convenient in engineering practice.

Accumulated experience on the use of the Fr_t^* and $\bar{J}_s^*$ numbers in combination with other numbers of system (5) enables us to say about the development of a new efficient procedure of generalization of experimental data in disperse systems with suspended particles. The employment of this procedure, in many cases, makes it possible to transform the process of generalization of experimental data to a simple routine.

NOTATION

$\mathrm{Ar} = gd^3\rho_f(\rho_s - \rho_f)/\mu_f^2$, Archimedes number; c, specific heat; d, particle diameter; d_1, diameter of the disk; D_f, diffusion factor; D, diameter of the bed (standpipe); $\mathrm{Fr} = (u - u_{mf})^2/gH$, $\mathrm{Fr}_t = (u - u_t)^2/gH$, $\mathrm{Fr}_t^* = (u - u_t^*)^2/gH$, $\mathrm{Fr}_h = (u - u_{mf})^2/gh$, $\mathrm{Fr}_l = u^2/gl$, Froude numbers; $\mathrm{Ga} = gd^3\rho_f^2/\mu_f^2$, Galilean number; g, free fall acceleration; h, height above the gas distributor; H, height of the bed (standpipe); H_{mf}, height of the bed for $u = u_{mf}$; J_s, specific mass particle flux; $\bar{J}_s = J_s/\rho_s(u - u_t)$ and $\bar{J}_s^* = J_s/\rho_s(u - u_t^*)$, dimensionless mass particle fluxes; L, bed height or size; l, height of the mass-transfer sensor; $\mathrm{Nu} = \alpha d/\lambda_f$, Nusselt number; p, pressure; Δp, head loss; $\mathrm{Pr} = c_f\mu_f/\lambda_f$, Prandtl number; $\mathrm{Re} = ud\rho_f/\mu_f$, Reynolds number; $\mathrm{Sc} = \mu_f/\rho_f D_f$, Schmidt number; $\mathrm{Sh} = \beta d/D_f$, Sherwood number; T, temperature; u, gas-filtration rate; u_t^*, velocity of particle drift under constrained conditions ($u_t^* \to u_{mf}$ when $\varepsilon \to \varepsilon_{mf}$ and $u_t^* \to u_t$ when $\varepsilon \to 1$); x, current coordinate along the height of the cylinder (counting from the lower end); α, heat-transfer coefficient; β, mass-transfer coefficient; ε, porosity of the bed; ε_p, packing-free fraction of the bed volume; θ, shape factor of the particle; λ_f, thermal conductivity of the gas; μ_f, dynamic viscosity of the gas; ρ, density. Subscripts: b, gas bubble; c-c, conductive-convective; f, gas; fb, superbed space; mf, onset of fluidization; p, packing; s, particles; t, condition of the drift of a single particle.

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