

An analysis is presented of critical comments regarding the packet theory of fluidized-bed heat transfer.

A series of articles has been published in recent years [1-5], particularly in the *Inzhenerno-Fizicheskii Zhurnal*, containing critical comments with regard to the packet theory of fluidized-bed heat transfer. In the most recent of these [5], our expression

$$\alpha = \frac{1 - f_0}{R_c + 0.5 \sqrt{\frac{\pi \tau_c}{\lambda_p \rho_p c_m}}} + \alpha_{\text{conv}} \quad (1)^*$$

is analyzed and our experimental results, including empirical expressions for  $\tau_c$  and  $f_0$ ,

$$\tau_c = 0.44 \left[ \frac{(w - Aw_{\text{cr}}^2)}{gd} \right]^{-0.14} \left( \frac{d}{D} \right)^{0.225}, \text{ sec.} \quad (2)$$

$$f_0 = 0.33 \left[ \frac{(w - Aw_{\text{cr}}^2)}{gd} \right]^{0.14} \quad (3)$$

are used. The extent to which these critical comments actually relate to our equations (1)-(3) should be discussed.

§1. "According to the comparatively widely accepted packet theory ([6] of the article cited), convective heat transfer is considered negligible" [3]. This assertion, in various forms, is found in all the articles [1-5]. In contrast, it is stated in [7] that the authors of [1-5] "have proposed and experimentally verified a new hydrodynamic theory of fluidized-bed heat transfer. It provides an essentially new approach to the solution of many important fluidized-bed and vibrating fluidized-bed problems, and, in particular, a new explanation of the acceleration of fluidized-bed heat and mass transfer," proceeding from the assumption that "localized gas flows play an essential role in fluidized-bed surface heat and mass transfer. These flows occur along the submerged surface with velocities which exceed filtration rates by an order of magnitude" ([8], p. 27).

Many packet models are presently known [6, 9-16], differing from each other and from the original primitive Mickley model [6, 16]. They contain various evaluations of the role of convection. According to our experimental data [17, 18], which serve as the basis for Eq. (1), the convective component of the overall heat-transfer coefficient increases from 5-15% for 0.1-mm particles of 90-95% for those above 4-5 mm. The experimental values for  $\alpha_{\text{conv}}$  given in [18] agree fairly well with those calculated from the expression derived in [11] for  $\alpha_{\text{con}}$ . † The authors of [3], in discussing the inclusion of convection by "the packet theory advocates," refer only to an old American article [6] in which convective heat transfer is not considered at all, and in analyzing Eq. (1) in [5] they discard  $\alpha_{\text{conv}}$ . In this sense, they reduce Eq. (1) to the old Mickley equation.

\* More precisely, Syromyatnikov [5] analyzes only the conductive portion of (1), which is related to packet heat transfer (editor's note).

† The author does not relate this expression ( $\text{Nu} = 0.0175 \text{Ar}^{0.46} \text{Pr}$ ) to packet heat transfer; it lacks the appropriate parameters (editor's note).

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The assertion that "convective heat transfer is considered negligible" is, therefore, not related to Eq. (1). On the contrary, it follows from the numbers cited above that, in agreement with this equation, convection is the decisive factor in a coarse-particle bed, although it is not significant in a fine-particle bed.

No quantitative data for  $\alpha_{\text{conv}}$  which might be compared with the results of our equations are presented in [1-5].

§2. In analyzing Eqs. (2) and (3), Syromyatnikov [5] concludes that "the heat-transfer coefficient for a developed fluidized bed is self-modeling with respect to  $\tau_c$  and  $f_0$ ." Substituting the values of  $f_0$  and  $\tau_c$  in (1), and discarding  $R_c$  and  $\alpha_{\text{conv}}$ , he finds that filtration rate and particle size "completely disappear" from this equation. In his opinion [5], this testifies to "the lack of correspondence between the basic packet theory equation and the model on which it is based."

It follows from Eqs. (2) and (3) that the term in the denominator of (1) is

$$\frac{0.5}{1-f_0} \sqrt{\frac{\pi\tau_c}{\lambda_p \rho_p c_M}} = \frac{0.337}{(1-f_0) \sqrt{\lambda_p \rho_p c_M f_0}} \left(\frac{d}{D}\right)^{0.112} \quad (4)$$

As  $f_0$  varies from 0 to 1, this term varies from  $\infty$  to  $\infty$ , passing through a minimum in the intense fluidization region (at  $f_0=0.33$ ) and remaining practically constant over the range  $f_0=0.2-0.5$ .

In accordance with this, the heat-transfer coefficient of (1) increases with increased fluidization rate from  $\alpha_{\text{conv}}$  at  $f_0=0$  to a maximum, and then begins to decrease slowly, both from the increase in (4) and the increase in the ratio  $R_c/(1-f_0)$  [Syromyatnikov [5] does not consider the latter effect, or analyzes Eq. (1) without  $R_c$ ]. All experiments yield this relationship between heat-transfer coefficient and fluidization rate, which is convincing evidence of the correctness of the assumptions underlying Eq. (1).

The physical meaning of this "self-modeling" was disclosed in [6]; with increased fluidization rate, the fraction of contact time  $f_0$  between sensor and gas bubbles increases, but the contact time  $\tau_c$  with the surface of the individual particle packet decreases.

In the experiments, as generalized by Eqs. (2) and (3), the particle size affects the value of  $\alpha$  in Eq. (1) chiefly through  $\alpha_{\text{conv}}$  and the contact resistance  $R_c$ , which increases linearly with increased  $d$  [11, 19]. Syromyatnikov [5] examines only the effect of particle diameter on the term (4), i.e., he actually analyzes the old Mickley model. The assertion that the effect of particle diameter is not considered "in the modified equation proposed by the author" (1) is incorrect.

§3. "For all fluidization numbers ( $W=1-8$ ), structural and hydrodynamic conditions ( $\epsilon > 0.7$  and  $w > w_{\text{cr}}$ ) for plates are created such that the fluidized bed goes from two-phase to a dilute phase (pneumatic transport), i.e., a situation in which the mechanism assumed in the packet theory is not considered reliable" [1]. In accordance with this, it is stated in [2] that the surface is usually in contact with a discrete phase (gas layers or bubbles) and not with particle packets.

This is apparently a question of difference in terminology, since the authors of [1-5] accept the quantitative relationships obtained by the packet model advocates. In [20] a comparison is made between the time-averaged porosity values, measured with x rays in an uncontaminated bed, with those calculated from the expression

$$\epsilon = f_0 + (1-f_0)\epsilon_p \quad (5)$$

Values for the fraction of contact time of surface with bubbles,  $f_0$ , and with particle packets,  $(1-f_0)$ , are taken from Mickley and our studies, in neither of which was the contact time with a dilute phase considered at all. Good correlation was found in [20] between Eq. (5) and experimental data.

A more detailed analysis of the critical comments on our presentation will be given in the future.

#### NOTATION

$A$ , dimensionless coefficient which allows for nonuniform velocity distribution at the body surface;  $c_M$ , particle heat capacity;  $d$  and  $D$ , particle and calorimeter diameters;  $f_0$ , fraction of time during which the surface is in contact with gas bubbles;  $g$ , gravitational constant;  $R_c$ , contact thermal resistance;  $w$  and  $w_{\text{cr}}$ , actual and critical fluidization rates;  $W$ , fluidization number;  $\alpha$  and  $\alpha_{\text{conv}}$ , total and convective heat-transfer coefficients between fluidized bed and surface;  $\epsilon$  and  $\epsilon_p$ , time-averaged porosities of

fluidized bed (at a given point) and particle packet;  $\lambda_p$  and  $\rho_p$ , particle packet thermal conductivity and density;  $\tau_c$ , contact time between particle packet and surface.

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