13. A. P. Burdukov and V. E. Nakoryakov, "Heat transfer from a cylinder in a sound field at Grashof numbers approaching zero," Zh. Prikl. Mekh. Tekh. Fiz., No. 1, 119-124 (1965).
14. A. P. Burdukov and V. E. Nakoryakov, "Influence of oscillations on the mass transfer from a sphere at large Prandtl numbers," Zh. Prikl. Mekh. Tekh. Fiz., No. 3, 158-160 (1967).
15. Chingfeng Chang and W. Schowalter, "Flow near an oscillating cylinder in dilute viscoelastic fluid," Nature, 252, No. 5485, 686-688 (1974).
16. C. Hill, "Nearly viscometric flow of viscoelastic fluids in the disk and cylinder system," Trans. Soc. Rheol., 16, No. 2, 213-247 (1972).
17. S. Rosenblat, "Reversal of secondary flow in non-Newtonian fluids," J. Fluid Mech., 85, Part 2, 387-400 (1978).
18. Chingfeng Chang, "Boundary layer analysis of oscillating cylinder flow in a viscoelastic liquid," J. Appl. Math. Phys., 28, 283-288 (1977).
19. K. Walters, "The solution of flow problems in the case of materials with memory," J. Mech., 1, No. 4, 479-486 (1962).
20. R. J. Hansen, "The reduced drag of polymer solutions in turbulent and transient laminar shear flows," Trans. ASME, Ser. I: J. Fluids Eng., 95, No. 1, 23 (1973).
21. D. Beard and K. Walters, "Elastico-viscous boundary-layer flows," Proc. Cambridge Philos. Soc., 60, 667-674 (1964).
22. V. P. Popov, N. A. Pokryvailo, and V. K. Gleb, "Measurement of the local transient flow velocity of a liquid by an electrochemical technique," in: Research on Transient Heat and Mass Transfer [in Russian], Nauka i Tekhnika, Minsk (1966), pp. 238-247.
23. R. Lemlich and M. Rao, "The effect of transverse vibration on the convection from horizontal cylinder," Int. J. Heat Mass Transfer, 8, No. 1, 27-33 (1965).
24. Z. P. Zhul'man, N. A. Pokryvailo, A. S. Sobolevskii, and T. V. Yushkin, "Convective mass transfer of a cone and dynamic characteristics of an electrodiffusion anemometer in a nonlinearly viscous fluid flow," Inzh.-Fiz. Zh., 30, No. 3, 456-465 (1976).
25. V. P. Epifanov, "Acoustical studies of aqueous polyoxyethylene solutions," Vysokomol. Soed., No. 4, (20)A, 942-946 (1978).
26. D. James, "A method for measuring normal stresses in dilute polymer solutions," Trans. Soc. Rheol., 19, No. 1, 67-80 (1975).

HYDRODYNAMICS OF A FLUIDIZED BED IN THE INTERTUBE SPACE OF STAGGERED AND IN-LINE TUBE BUNDLES

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UDC 66.021.33

The article presents the results of the experimental investigation of the effect of the horizontal and vertical pitches of tubes on the hydrodynamics of a fluidized bed. A formula is presented for calculating the mean porosity of the bed in the intertube space of tube bundles with optimum arrangement.

One of the most promising recent trends in improving boilers is the low-temperature combustion of solid fuels in a fluidized bed by removing the heat from the combustion zone with the aid of cooling surfaces made in the form of horizontal tube bundles in staggered or in-line arrangement. The results of investigations of the gasification and combustion of solid fuel in suspended state [1] indicate that the zone of active combustion in such systems does not exceed 200 mm from the level of the gas-distributing grid. Therefore, if heat-exchange surfaces are to be situated in such a zone to ensure low-temperature combustion of the fuel, the surfaces have to be compact and optimally arranged.

The object of the present work is to investigate the hydrodynamics and the structure of

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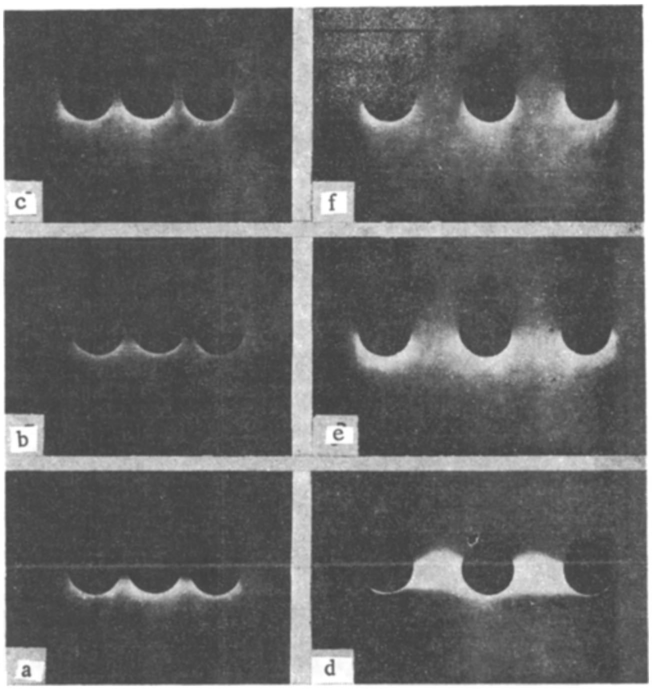

Fig. 1. Effect of the horizontal pitch on the nature of the flow of the bed in the intertube space: a–c) $s_h = 1.2d_{tu}$; d–f) $2d_{tu}$; a) $W = 1.2$; d) 1.05; b, e) 2; c, f) 3.

the fluidized bed in the intertube space in order to work out recommendations for the most rational arrangement of the tubes in the bundle.

The flow of a fluidized bed past tube bundles was investigated by visual observation and x-ray photography. The experiments were carried out with bundles of horizontal tubes of 25-mm diameter in an apparatus whose size in plan was 50 × 250 mm.

The apparatus with the fluidized bed and the tubes arranged in it was examined by a broad x-ray beam. The fluidizing agent was air of room temperature. The solid phase was monofraction particles of fireclay and polystyrol with diameters of 0.7, 1.3, and 2.2 mm. The height of the packed bed was 200 mm. The minimum distance between the tubes in the lowest row of the bundle and the gas-distributing grid was 50 mm.

To reveal the effect of the horizontal pitch s_h on the nature of the flow around the tubes, a single-row bundle of three tubes was used, its pitch being changed from $s_h = 1.2d_{tu}$ to $3d_{tu}$ (Fig. 1).

With $s_h = 1.2d_{tu}$, it was found that with increasing filtering rate, the particles under the lower surface of the tubes were gradually expelled by the air and a common gas cavity formed. With $W \approx 1$, the air in the form of bubbles escaped from it, flowed around all tubes as a whole (Fig. 1a), and the layer of particles lying in the intertube space and on the upper half of the tubes remained motionless. A further increase of the speed (Fig. 1b, c) practically did not change the pattern of the flow, only the frequency of merging of the air cavity increased, and consequently also the intensity of motion of the bubbles washing the outer surface of the outer tubes in the bundle. The obtained pattern explains the fact, noted in [2], that the heat-transfer coefficient decreases in tube bundles with $s_h < 2d_{tu}$.

When the horizontal pitch increases to $2d_{tu}$ (Fig. 1d–f), the flow pattern changes: at a speed close to the rate, the onset of fluidization, the gas cavity does not form under the tubes but between them (Fig. 1d). When $W > 1$, the air flows from this cavity in the form of bubbles that rise in the intertube space, not flowing around the outer surfaces of the outer tubes that are also the outer surfaces of the bundle; there the particles lie motionless, and with increasing filtering rate ($W > 1.2$), they begin to move but less intensively than the particles inside the bundle.

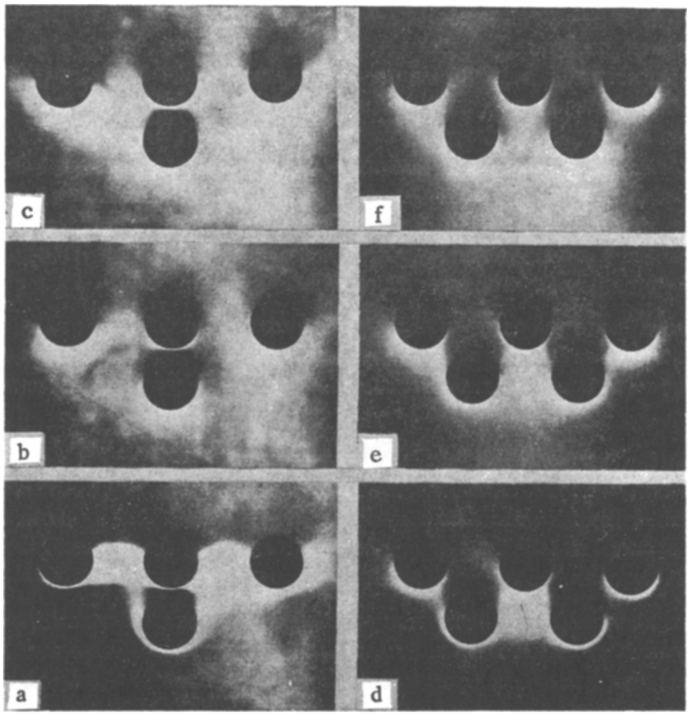

Fig. 2. Flow pattern of the fluidized bed in bundles of tubes with $s_v = 1.2d_{tu}$ and $s_h = 2d_{tu}$; a, d) W = 1.05; b, e) 2; c, f) 3.

The regularities of flow of the fluidized bed around a bundle of tubes with horizontal pitch equal to $3d_{tu}$ fully coincide with those for a single tube [3]. It should be pointed out that the intensity of heat transfer does not change either when the pitch increases to $s_h > 2d_{tu}$ [2, 4].

The effect of the vertical pitch s_v on the hydrodynamics of the fluidized bed was investigated in a bundle of tubes in which s_v changed from $1.2d_{tu}$ to $3d_{tu}$, and s_h remained constant and equal to $2d_{tu}$.

With the in-line as well as with the staggered arrangement of the tubes, the vertical pitch has practically no effect on the nature of the flow of the bed in the intertube space when $s_v \geq 2d_{tu}$. The authors of [5], who investigated the heat exchange between bundles of tubes and a fluidized bed, also noted that the effect of the vertical pitch on the heat-transfer coefficient is negligible.

Only with $s_v < 2d_{tu}$ (Fig. 2) were there some peculiarities. The gas cavity, which forms under the lower surface of the tube lying higher than the row, is thicker with the in-line arrangement (Fig. 2a-c), and the "cap" of particles lying motionlessly on the low-lying tubes is smaller than with $s_v = 2d_{tu}$ (Fig. 3a-c).

With $s_v < 2d_{tu}$ and staggered arrangement (Fig. 2d-f), the chain of bubbles flowing around the tube of the lowest row enters the gas cavity forming under the tube of the higher row, forcing the latter to pulsate intensively. With increasing s_v, this effect decreases.

If we compare the flow of the bed in staggered and in-line bundles, we note that in the staggered arrangement of the bundle, the flow around the tubes inside the bundle and on the outside is approximately equal, and the entire bed is more mobile than with the in-line arrangement of the tubes where most of the fluidizing agent passes through the inside of the bundle. It was noted that the transition of the entire bed into the fluidized state occurs with lower draft head (by ≈ 5%) when the arrangement of the bundle in the bed is staggered. This fact is illustrated by a comparison of Figs. 3a and 3d in which the instant of transition to the fluidized state is recorded. In the staggered bundle the particles are already in motion, in the in-line bundle (with the same draft head) the particles are still motionless (fluidization and even spouting of the particles occurs only at the surface of the tubes, which was previously noted by the present authors [6]).

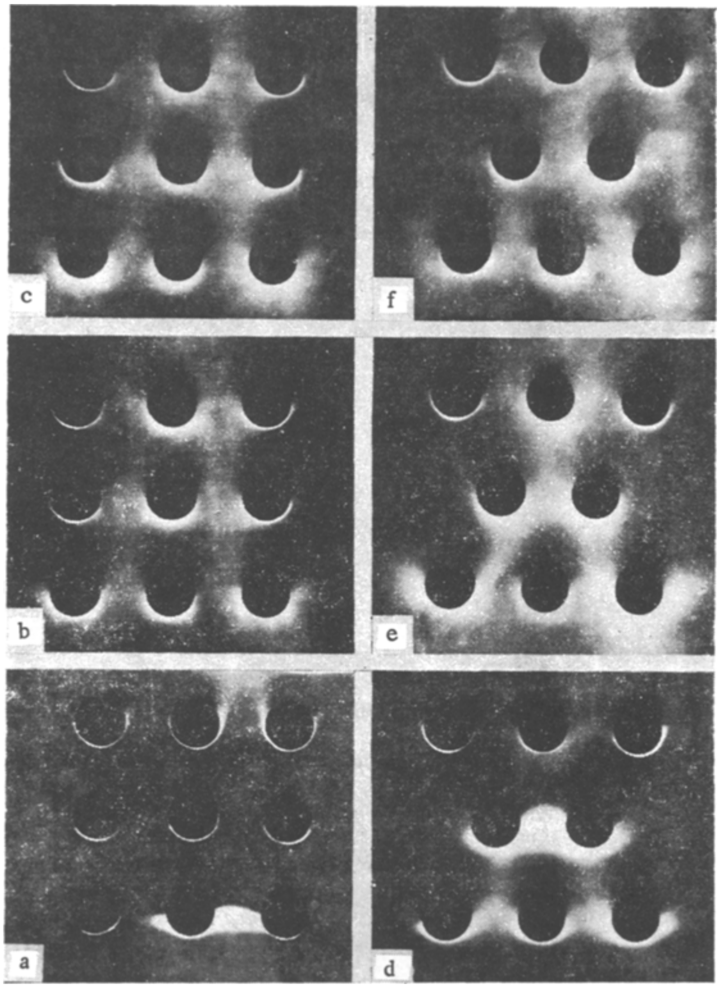

Fig. 3. Flow pattern of the fluidized bed in in-line (a-c) and staggered (d-f) bundles of tubes with $s_h = s_v = 2d_{tu}$; a, d) W = 1.05; b, e) 2; c, f) 3.

If we compare the rates of the onset of fluidization of the unbraked bed and of the bed braked by the tubes immersed in it, we find that the rate of the onset of fluidization of the braked bed is greater (in our experiments it was 5-10% greater, depending on the arrangement and number of tubes situated in the bed) than of the free bed. This can be explained by the phenomenon discovered by the authors of [7, 8], viz., the occurrence of additional (adjoint) gas streams from the core of the bed into the near-wall zone of the bodies situated in the bed; this causes a rearrangement of the speed profile of the gas in such a way that the maximum speed occurs at the surface of the body, and the minimum in the core of the bed. This redistribution of the gas flow rates is particularly noticeable at filtering rates close to the onset of fluidization. Therefore, there is also spouting of the particles at the surface of bodies while the particles within the bulk of the bed are still motionless.

The qualitative data on the hydrodynamics of the fluidized bed obtained by us and the quantitative results on heat exchange [2, 4, 5] in tube bundles permit the conclusion that the optimum arrangement of tubes in a bundle from the point of view of its compactness, intensity of heat exchange, and the hydrodynamics of the bed in the intertube space corresponds to a horizontal pitch in the range $s_h = (2-3)d_{tu}$ and vertical pitch $s_v = (1.5-2)d_{tu}$. The preferable arrangement of the tubes in a bundle is the staggered one.

The hydrodynamics of the fluidized bed determines its structure whose chief characteristic is the porosity of the bed.

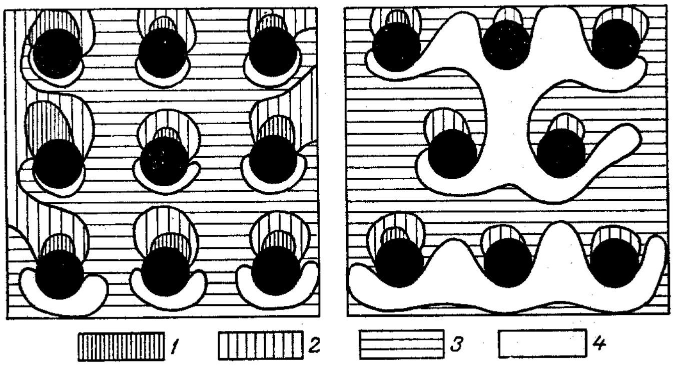

Fig. 4. Distribution of the porosity of the bed in the intertube space with $W = 2$: 1) $\varepsilon = \varepsilon_0$; 2) $\varepsilon_0 \leqslant \varepsilon < 0.6$; 3) $0.6 \leqslant \varepsilon < 0.7$; 4) $0.7 \leqslant \varepsilon < 1.0$.

Gel'perin et al. [2] measured the pressure gradient with the aid of impulse pipes placed at different points of the bed containing horizontal bundles of tubes, and the mean porosity in the zone of the bundle was calculated from this gradient. This yielded an equation which was checked in the interval $295 \leqslant \mathrm{Ar} \leqslant 3730$ (i.e., d_r was not larger than 0.352 mm):

$$\varepsilon_{\mathrm{bun}} = e\left(\frac{w}{w_0}\right)^z,$$

where

$$e = \left(1 - \frac{0{,}37\,\mathrm{Ar}}{\mathrm{Ar} - 30}\right)\varphi^{-\frac{0{,}37\,\mathrm{Ar}}{\mathrm{Ar}+270}}, \quad z = \lg\frac{\varepsilon_0}{e}\Big/\lg\frac{w_0}{w_v},$$

but which is fairly complicated for practical use. We therefore determined the porosity of the fluidized bed in the zone of staggered and in-line bundles of tubes with $s_h = s_v = 2d_{tu}$ by the method of photometering radiographs [9].

The distribution of the porosity of the bed in the zone of tube bundles corresponding to the hydrodynamic pattern shown in Fig. 3c, f is presented in Fig. 4. It can be seen from the figure that with the staggered arrangement, the fluidized medium at the surface of the tubes is more homogeneous. There are practically no sections of tubes on which the bed is motionless (i.e., where $\varepsilon = \varepsilon_0$), whereas with the in-line arrangement, such sections occur on each tube.

In staggered and in-line tube bundles, the mean porosity in the zone shown in Fig. 4 was determined by graphic integration. An analysis of the porosity values showed that it depends on the particle diameter, the filtration rate, and the arrangement of the tubes in the bundle. With the same fluidization numbers, the porosity in the zone of an in-line bundle was somewhat lower than that of a staggered bundle (by 6% which, however, lies within the limits of the experimental accuracy).

Processing of the experimental data in criterial form yielded the following expression for the mean porosity of a staggered bundle:

$$\frac{1 - \varepsilon_{\mathrm{bun}}}{1 - \varepsilon_0} = 1{,}25\,W^{-0.4}\,\mathrm{Ar}^{-0.03},$$

which is correct in the ranges $1.2 \leqslant W \leqslant 5$, $29{,}200 \leqslant \mathrm{Ar} \leqslant 406{,}000$.

NOTATION

$\varepsilon_{\mathrm{bun}}$, ε_0, porosity of the bed in the intertube space of the bundle and the packed bed; w_0, w_v, w, rate of onset of fluidization, falling of particles, and filtration; φ, proportion of the free section of the apparatus; $W = w/w_0$, fluidization number; $\mathrm{Ar} = g d_r^3(\rho_r - \rho)/\nu^2\rho$, Archimedes number.

LITERATURE CITED

1. N. I. Syromyatnikov and V. F. Volkov, Processes in a Fluidized Bed [in Russian], Metallurgizdat, Moscow (1959).
2. N. I. Gel'perin, V. G. Ainshtein, and A. V. Zaikovskii, "Hydraulic and heat-exchange characteristics of a fluidized bed with horizontal tube bundles," Khim. Neft. Mashinostr., No. 3, 17-21 (1968).
3. N. J. Syromyatnikov, V. M. Kulikov, and V. N. Korolev, "Structural and hydrodynamic conditions of fuel combustion in a low-temperature fluidized bed," Inst. Fuel, December, 169-171 (1977).
4. A. I. Tamarin, S. S. Zabrodskii, and Yu. G. Epanov, "Investigation of heat exchange between a horizontal staggered tube bundle and a fluidized bed," in: Heat and Mass Exchange-V [in Russian], Vol. 6, Minsk (1976), pp. 117-122.
5. N. I. Gel'perin, V. G. Ainshtein, and A. A. Korotyanskaya, "Heat exchange between a fluidized bed and staggered bundles of horizontal tubes," Khim. Promy., No. 6, 27-31 (1968).
6. V. N. Korolev and N. I. Syromyatnikov, "Flow around bodies in fluidized media," Dokl. Akad. Nauk SSSR, 203, No. 1, 58-59 (1972).
7. V. N. Korolev, "Investigation of the gas speeds in a fluidized bed with a plate immersed in it," in: Transactions of the S. M. Kirov Urals Polytechnic Institute. Heat and Mass Transfer and Nonequilibrium Thermodynamics of Disperse Systems [in Russian], No. 227, Sverdlovsk (1974), pp. 85-90.
8. N. B. Kondukov, N. I. Frenkel', S. A. Nagornov, et al., "Some peculiarities of the hydrodynamics and external heat exchange in a fluidized bed," Dokl. Akad. Nauk SSSR, 224, No. 5, 1138-1140 (1975).
9. N. I. Syromyatnikov and V. N. Korolev, "Distribution of porosity over the height of a fluidized bed near a plate immersed in it," Teor. Osn. Khim. Tekhnol., 8, No. 6, 930-933 (1974).

FINE-SCALE MIXING IN A GAS-FLUIDIZED BED OF FINE PARTICLES

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The coefficients of diffusion of the particles and gas in the dense phase of a fluidized bed and the mean squares of the components of their pulsation velocity are analyzed with direct particle collisions neglected.

The particles and the fluidizing medium in a homogeneous fluidized bed or the dense phase of an inhomogeneous bed undergo intense chaotic ("pseudoturbulent") motions, the presence of which leads to the fact that the effective values of the transfer coefficients in the dense phase usually far exceed the values of the corresponding coefficients for the homogeneous materials of the phases. Although in actual inhomogeneous systems the role of such fine-scale mixing can be insignificant within the limits of the bed as a whole compared with the role of the mixing due to the circulation of the phases and bubbling (see [1], for example), it is important precisely for the determination of such quantities as the average time the particles remain near the surface of bodies submerged in the bed and in contact with elements of the dense phase ("packets") and the intensity of particle exchange between the surface zone and the cores of packets.

In particular, the latter quantities determine the intensity of heat exchange between the bed and a submerged surface, and knowledge of their dependence on the operating and physical parameters is entirely necessary for the generalization and further development of the existing particular models of external heat exchange in a fluidized bed [2]. And the

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