$$\times\left[\frac{2l}{c}\sum_{p=1}^{\infty}\frac{I_1(Rp)\sin^2\frac{p\pi c}{l}}{\pi^2p^3\,\mathrm{Bi}\,I_0(Rp)\left[1+\frac{p}{\mathrm{Bi}}\frac{I_1(Rp)}{I_0(Rp)}\right]}-\frac{c}{2l}\right]^{-1}. \quad (12)$$

It depends on the coefficient of convective heat transfer of the transducer (Fig. 3), which may vary broadly during the measurements.

Thus, internal heating of a cylindrical film-type transducer in a hot-wire anemometer is one of the most effective means of improving its metrological characteristics.

NOTATION

$T(r, z, \varphi)$, temperature of transducer substrate, °K; r, z, φ, coordinates of a point in the cylindrical system; a, diffusivity, m^2/sec; c, specific heat, J/kg·deg; γ, density of the body, kg/m^3; ω, specific power of the internal heat source, W/m^3; α, coefficient of convective heat transfer, $W/m^2 \cdot K$; λ, thermal conductivity of substrate, W/m·K; g, quantity of heat released per unit of time per unit of surface of the film by the current passing through it, $J/sec \cdot m^2$; T_{md}, temperature of the medium flowing around the cylinder, °K; p, Fourier transform parameter; $I_0(Rp)$, $I_0(rp)$, $I_1(Rp)$, $I_1(rp)$, modified Bessel functions.

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COMPARISON OF MAXIMUM COEFFICIENTS OF HEAT TRANSFER TO A SURFACE SUBMERGED IN A FLUIDIZED BED WITH AN ESTIMATE OBTAINED FROM AN EMPIRICAL FORMULA

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Empirical coefficients of heat transfer from a fluidized bed to bodies of various shapes are compared with coefficients calculated from a formula which considers heat transfer by particle and gas convection and by radiation.

As is known, heat transfer occurs between a fluidized bed and a body immersed in it by three different mechanisms: particle convection (this mechanism is sometimes referred to as conduction), gas convection, and radiation. These mechanisms are interrelated, but they are most often analyzed individually, permitting additivity, in order to simplify analysis and compare theoretical formulas. Given the current level of our knowledge of the complex process of heat transfer in fluidized systems, this approach is obviously the only proper approach.

The maximum heat-transfer coefficient α_{max} is of the greatest practical interest. This value is reached at the optimum fluidization velocity w_{opt}. The dependence of α on w has a maximum with a fairly gentle slope, so the heat-transfer coefficient changes little at velocities above the optimum value. It was noted in [1] that the difference $w_{opt} - w_c \simeq 0.35$ m/sec for most particles. In a bed of coarse particles, this difference is not large compared to the critical velocity w_c, and the optimum velocity turns out to be close to the free-falling velocity only in a bed of particles finer than 0.1 mm. However, in this case the dependence of the heat-transfer coefficient on the fluidization velocity (before it reaches

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its optimum value) often proves to be irreproducible, since it depends on a large number of random factors. Thus, the base value is again α_{max}.

The main heat-transfer mechanism is frequently particle convection. Many formulas have been suggested in the literature to calculate α_{max} for this mechanism, such as those proposed by Zabrodskii [2] and Varygin and Martyushin [3]. Gas convection becomes more important with an increase in particle size (and it becomes the main mechanism when d > 4-5 mm). To find α_{max} for this mechanism, the following empirical formula was proposed [4]

$$\mathrm{Nu}_{conv} = 0.009\mathrm{Ar}^{0.5}\mathrm{Pr}^{0.33}, \tag{1}$$

which essentially establishes a relationship between the same dimensionless numbers as do the formulas, such as the following, which describe particle convection [3]:

$$\mathrm{Nu}_{max} = 0.86\mathrm{Ar}^{0.2} \tag{2}$$

(the Prandtl number for the gas mechanism changes very little, so the exponent of Pr in (1) is unfounded. However, its accuracy is not really important).

Since heat transfer by the gas and particles is interrelated, the total effect of gas and particle convection is better accounted for [5] by the formula

$$\mathrm{Nu}_{max} = 0.85\mathrm{Ar}^{0.19} + 0.006\mathrm{Ar}^{0.5}\mathrm{Pr}^{0.33}, \tag{3}$$

in which all of the thermophysical parameters pertain to the mean temperature $t = 0.5(t_{fb} + t_w)$.

The studies in [6] made it possible to recommend the following relation for calculating the radiative component

$$\alpha_r = 7.3\sigma_0\varepsilon_m\varepsilon_w T_w^3. \tag{4}$$

Thus, the final formula for calculating the coefficient of external heat transfer in a fluidized bed has the form

$$\alpha_{max} = \frac{\lambda}{d}(0.85\mathrm{Ar}^{0.19} + 0.006\mathrm{Ar}^{0.5}\mathrm{Pr}^{0.33}) + 7.3\sigma_0\varepsilon_m\varepsilon_w T_w^3. \tag{5}$$

The figure compares the experimental data from several investigators (the data without the symbols referring to sources in the literature is ours) with data calculated with Eq. (5). The emissivity of the material of the bed particles ε_m and the surface of the transducer wall ε_w for the prescribed temperatures was taken from the data in [7, 8].

In the works [9-12], the results of which are used in Fig. 1a, the transducers for studying heat transfer were small-diameter horizontal water-cooled tubes. The nonuniformity of heat transfer about their perimeter was slight, and the mean heat-transfer coefficients over the surface agree with the results calculated with Eq. (5).

In tests in [9] with a coiled tube with an outside diameter D = 6 mm, the temperature of the surface t_w according to the calculations was slightly higher than 100°C. The bed of particles of corundum with d = 0.5 mm (points 1, 2), magnesium oxide with d = 2.5-3.0 mm (3), and Alundum with d = 5-7 mm (4) was fluidized by products of the combustion of natural gas. The temperature of the bed t_{fb} in the tests ranged from 350 to 1250°C. To ensure a surface with a high and constant emissivity during the tests, the transducer was subjected to a preliminary heat treatment by the method described in [3]. Only point 2 was obtained with a coiled tube galvanically coated with a layer of nickel about 10 μm thick.

In tests [10] with steel tubes with D = 16-21 mm (ε_w = 0.8), the temperature of the bed of high-alumina refractory, with d = 0.8 (5), 1.3 (6), and 1.8 (7) changed in the range 600-1200°C as a result of its fluidizing by natural-gas combustion products. The studies in [11] were performed with a coiled copper tube with D = 8 mm. Corundum particles with d = 0.12 and 0.32 mm were fluidized by air (8 and 9) and steam (10) and vapor (11) with a temperature of 120-150°C.

The work [12] studied heat transfer to a coiled copper tube with an outer diameter D = 4 mm in a bed consisting of a vanadium catalyst with d = 0.13 (12), 0.38 (13), 1.5 (14), 2.5 (15), 3.5 (16), and 4.5 (17), an aluminum-nickel catalyst with d = 1.5 (18), 2.5 (19), and 3.5 (20), an iron-chromium catalyst with d = 0.38 (21) and 1.5 mm (22), coke with d = 1.5 mm (23), silica gel with d = 0.38 (24) and 1.5 mm (25), marble with d = 0.38 (26) and 1.5 mm (27), and quartz with d = 0.38 (28) and 1.5 mm (29). The temperature in the bed was maintained at 140°C. The results were 12.5% higher than ours, since the authors of [12] de-

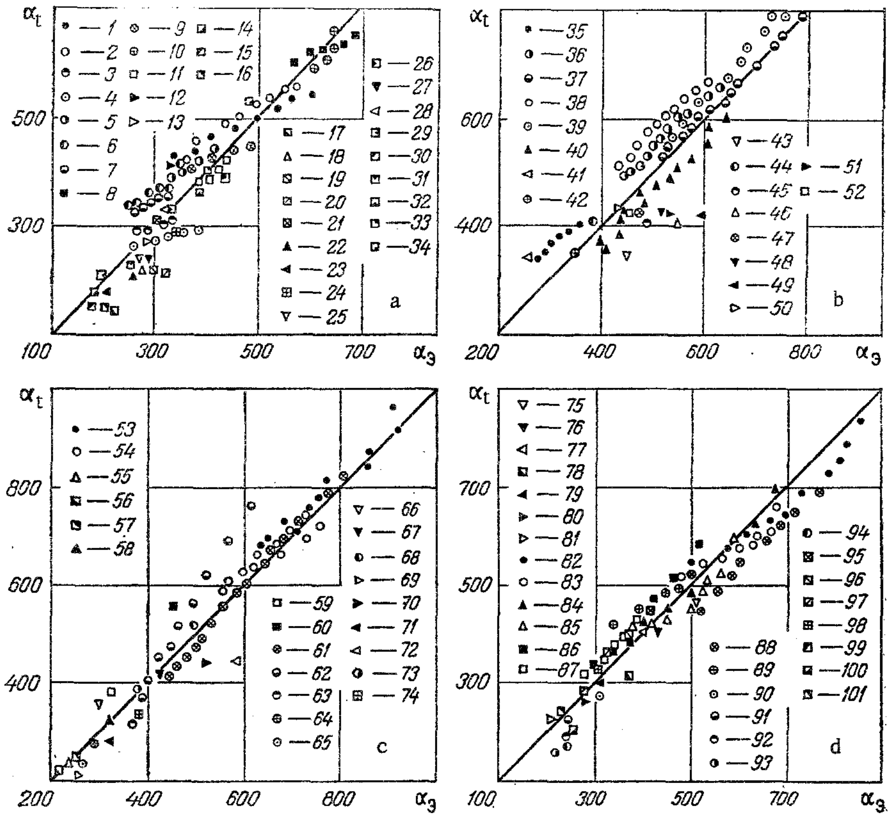

Fig. 1. Comparison of calculated α_t ($W/m^2 \cdot K$) and experimental α_e ($W/m^2 \cdot K$) heat-transfer coefficients obtained with an optimum fluidization velocity: a) mean values over the surface of horizontal tubes (D = 4-23 mm, d = 0.12-7 mm, t_{fb} = 30-1250°C, t_w = 50-150°C); b) maximum values about perimeter of horizontal cylinders (D = 89-220 mm, d = 0.28-0.5 mm, t_{fb} = 50-1000°C, t_w = 100-900°C); c) heat transfer to plates inclined at an optimum angle and to vertical tubes (plates D = 50, 80 × 80, and 160 × 220 mm, d = 0.12-2.0 mm, t_{fb} = 30-1300°C, t_w = 100-1100°C; vertical tubes D = 13-32 mm, d = 0.13-0.88 mm); d) mean values over the surface of spheres (D = 20-60 mm, d = 0.14-3.5 mm, t_{fb} = 350-1050°C, t_w = 100-1000°C).

termined the heat-transfer surface in accordance with the mean diameter of the tube rather than the outside diameter.

The authors of [13], the results of which are also shown in Fig. 1a, fluidized a bed of quartz sand with d = 0.22 mm (30) with dry air and determined the coefficient of heat transfer from a thick-walled copper tube with D = 23 mm with a built-in electric heater. In [1], heat transfer was studied in shallow (height$\leqslant$50 mm) beds of porous particles of aluminum oxide with d = 1.1 mm (31) and sand with d = 0.345 (32), 0.253 (33), and 0.134 (34) at t_{fb} = 75-150°C. The transducer was a water-cooled steel tube with D = 14 mm.

With an increase in the diameter of horizontal cylinders submerged in a fluidized bed, the nonuniformity of the heat exchange about the perimeter becomes substantial due to the appearance of a stagnant zone on the cylinder and a low-density zone under it. The mean heat flux about the perimeter decreases with an increase in cylinder diameter. For large horizontal cylinders, Eq. (5) predicts the maximum heat-transfer coefficients about the perimeter fairly well.

At high temperatures t_{fb} and t_w, the value of α_{loc} was found from the heating or cooling rate at 50°C intervals on a Nichrome cylinder. The emissivity of the surface in the temperature range investigated was 0.8-0.9. At low temperatures, the measurements were made by a stationary method on the heated section of the cylinder [14-16]. The results of measurements of the maximum α_{loc} are compared with the values calculated with Eq. (5) in Fig. 1b.

In the fluidization of the corundum particles with d = 0.5 mm by air (t_{fb} = 50°C), the preheated cylinder, with D = 89 mm, was cooled from 700 to 100°C (35), while during the fluidization with the natural gas combustion products, the cylinders with D = 159 and 219 mm were heated from 100 to 700°C at t_{fb} = 800°C (36 and 37) and to 900°C at t_{fb} = 1000°C (38 and 39); the cylinder with D = 159 mm was similarly heated in a bed of magnesium oxide particles with d = 1 mm at t_{fb} = 1000°C (40).

A 700 × 60 "flat" model was used with an air blast to study heat transfer from cylinders with D = 89 (41 and 44), 159 (42 and 45), and 219 mm (43 and 46) to corundum particles with d = 0.5 and 0.32 mm (t_{fb} = 50°C, t_w = 150°C). The same model (47) [14] and an enlarged unit 1.2 × 0.6 mm in cross section were used for tests on cylinders with D = 220 mm (corundum particle diameter d = 0.3 mm). In the last case, the 220-mm-diameter cylinders (48 and 50), as well as 125-mm-diameter cylinders (49 and 51) were positioned 750 mm [15] and 250 mm [16] above the axis of the bubble caps. The high values of the maximum α_{loc} at the 750-mm level in a bed 1 m deep is due to the significant increase in the size of the bubbles, which intensify mixing of the particles and heat exchange.

The authors of [14], by controlling the hydrodynamics of the bed near the surface of a cylinder with D = 220 mm through the installation of a deflector and a circular insert an optimum distance above and below, respectively, eliminated the stagnant and low-density zones and thus intensified and equalized heat exchange about the perimeter of the cylinder. In such cases, Eq. (5) can be used to calculate the mean heat-transfer coefficients over the surface (52).

The orientation of plates in a fluidized bed affects the hydrodynamics of flow about them and, hence, heat transfer. Figure 1c presents a comparison of heat-transfer coefficients calculated by Eq. (5) with experimental values for plates with optimum (from the point of view of heat transfer) angles of inclination. Also shown in data for small-diameter vertical tubes for which the coefficients of heat transfer are almost maximal.

In a high-temperature (t_{fb} = 1200°C) fluidized bed of corundum with d = 0.5 mm, the heat-transfer coefficients were found from the rate of heating of flat transducers measuring 80 × 80 mm and having a surface emissivity ε_w = 0.8-0.9 (53) and 0.1-0.2 (54) [6]. Heat-transfer coefficients were found in [17] in low-temperature (t_{fb} = 30°C) bed of glass (d = 1 mm (55)) and corundum (d = 2.0 (56), 1.25 (57), 0.5 (58), 0.32 (59), and 0.12 mm (60)) particles using a stationary method. The authors measured the electrically heated sections of plates measuring 160 × 220 mm.

The values of heat flow obtained in [18] from a high-alumina powder with d = 1.5-2.0 mm to a 16-mm-diameter disk inserted in a vertical circular plate with D = 40 mm were used to calculate heat-transfer coefficients. Here, we employed the same values of bed temperature, t_{fb} = 1300°C (61) and 1150°C (62), and wall temperature (t_w = 200-1100°C) as were cited in [18].

We also took data from [19, pp. 361, 362, and 347] accumulated by Vitt and Fetting in tests with a vertical tube with D = 13 mm in bed of sand with d = 0.32 (63), 0.45 (64), and 0.75 mm (65) and aluminum with d = 0.31 mm (66), as well as the data of Berg and his colleagues obtained with a tube with D = 32 mm in beds of particles of iron with d = 0.38 (67), sand with d = 0.13 (68), 0.2 (69), and 0.88 mm (70), silica gel with d = 0.5 mm (71), and glass with d = 0.16 mm (72) fluidized by air. The authors of [20] studied heat transfer from a bundle of vertical tubes to a bed of quartz sand with d = 0.25 (73) and 0.35 mm (74) fluidized by air.

In well-known works which have studied heat exchange between a fluidized bed and spheres immersed in it, the heat-transfer coefficient was determined from the rate of heating or cooling of transducers with D = 20 [3, 21] and 60 mm [22]. The mean value, over the surface, of the coefficient of heat transfer to such spheres α is compared in Fig. 1d with values calculated with Eq. (5).

In the work [3], a sphere was submerged in a bed of quartz sand with d = 0.14 (75), 0.2 (76), 0.22 (77), 0.43 (78), 0.52 (79), 0.65 (80), and 1.1 mm (81). The fluidizing agent was air.

The authors of [21] heated spheres with an emissivity ε_w = 0.8 and 0.02-0.07 in a bed of particles of fireclay with d = 0.35 (82 and 83), 0.63 (84 and 85), and 1.25 mm (86 and 87). The temperature of the bed was maintained at 850°C by burning natural gas.

In the tests in [22], the temperature of a bed of quartz sand with d = 0.34 (88) and 0.44 mm (89) was changed within the range t_{fb} = 500-1050°C by feeding flue gases into the furnace. Measurements were made at t_{fb} = 500°C in a bed of particles of iron—magnesium catalyst with d = 0.38 (90), 0.75 (91), 1.3 (92), 2.5 (93), and 3.5 mm (94), as well as in a bed of fireclay particles with d = 0.34 (95), 0.45 (96), 0.55 (97), 0.71 (98), 1.04 (99), 1.34 (100), and 1.6´ (101).

It follows from comparing the experimental coefficients of heat-transfer fluidized beds 0.05 to 1 m deep to bodies of different shapes with heat-transfer coefficients calculated from Eq. (5) that the latter is best used for engineering calculations of the coefficient α_{max} in beds of particles of different materials with sizes d = 0.12-7 mm up to the temperatures t_{fb} = 1300°C and t_w = 1000°C. The error of the calculations for the conditions of most experiments at low temperatures does not exceed 15-20% (it reaches 32% in certain cases [12]), while it is not greater than 10% for tests at high t_{fb} and t_w.

Equation (5) covers a broad range of experimental conditions and, moreover, the literature sources do not always specify the test conditions with the degree of accuracy necessary for the calculation. This fact, together with the error of the determination of the empirical values of the heat-transfer coefficient (which is sometimes quite substantial but far from always cited by the investigators) unavoidably reduces the probability of agreement between experimental data and results calculated with the proposed formula.

NOTATION

D, diameter of tube, cylinder, sphere, m; d, particle diameter, m; T, temperature, °K; t, temperature, °C; w, fluidization velocity, m/sec; α, heat-transfer coefficient, W/m²·K; ε, integral emissivity of the surface; λ, thermal conductivity, W/m·K; σ, radiation factor, W/m²·K⁴; Indices: c, critical; fb, fluidized bed; r, radiative; loc, local; m, material of particles; max, maximum; 0 pertains to a blackbody; opt, optimum; t, calculated; w, wall (heat-transfer surface); e, experimental. Criteria: Ar, Archimedes; Nu, Nusselt; Pr, Prandtl.

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EXPERIMENTAL STUDY OF THE THERMAL AND GASDYNAMIC PROPERTIES OF INSULATION WITH PERFORATED DIFFRACTING SCREENS

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An experimental study is made of the thermal, optical, and gasdynamic characteristics of a new cryogenic thermal insulation.

The reduction in the radiative and contact components of heat flow in vacuum-shield thermal insulation (VSTI) attained by improving the properties of the materials of the screens and interlayers has made it possible to improve the characteristics of VSTI's only up to a certain point. As was shown in [1-3], a further improvement in the effectiveness of VSTI's is related to the need to reduce heat transfer by gas molecules in their layers. In a first approximation, the pressure of the gases p_g in the layers of porous VSTI's is described by the relation [4]

$$p_g \approx \frac{W_0 (\delta - x)^2}{2D}. \tag{1}$$

It follows from Eq. (1) that one of the most promising methods of reducing the pressure is increasing the gas permeability of the VSTI packets. The perforated VSTI screens presently used for this purpose do not reduce gas pressure in the layers of the VSTI to the required level without an accompanying significant increase in radiant heat transfer [5, 6]. However, as was shown in [7], if the size of the holes in the metal screen is made less than half the wavelength of the incident thermal radiation, then the resulting diffraction screen, even with a porosity of about 90%, will be impermeable to radiation but at the same time permeable to the gas molecules. It follows from the theory in [7] that for cryogenic heat insulation the holes in the screens should be no larger than 2.5 μm. If the diffraction screens are made on the basis of metallized polymer films, then the thickness of the metallic coating in the channels should be close to the thickness of the metallized layer comprised of the outer surfaces of the screen.

The authors of [8] proposed the use of metallized nuclear filters as perforated diffraction screens (PDS). Such filters are obtained through the action of accelerated heavy ions,

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