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GAS-TO-PARTICLE HEAT TRANSFER IN VERTICAL PNEUMATIC CONVEYING OF GRANULAR MATERIALS IN THE REGION OF UNSTEADY-STATE PARTICLES MOTION

Summary. The results of investigations into interphase heat transfer in vertical pneumatic conveying in the region of steady-state and unsteady-state particles motion have enabled to work out a correlation describing the gas to-particle heat transfer, given by the relationship

$$Nu_p = A \cdot \beta_v^{-0,5911} \cdot Re_p^C$$

where

$$A = 0,00114 - 0,0094 \cdot \sqrt{1 - 1/X}$$

$$C = 0,8159 - 0,3159 \cdot \sqrt{1 - 1/X}$$

$$X = (U_g - u_s)/U_u$$

valid for: $180 < Re_p < 2440$; $0,00025 < \beta_v < 0,05$; $1 \leqslant X \leqslant 2$.

The relationship obtained reduces, for $X = 1$, to that obtained previously, holding in the region of steady-state motion of particles.

1. Introduction

Heat transfer between gas and solid particles, combined with simultaneous transport of these particles occurs very often in technological processes. One can mention here, e.g. installations for the regeneration of catalyst in the process of catalytic cracking, equipment employed in certain chemical coal processing technologies, driers and, finally, high-temperature heat exchangers. The granular materials participating in heat transfer are often thermally unstable or their physico-chemical properties vary unfavourably during heating. In such cases a correct design of pneumatic conveying with accompanying heat transfer is of particular impor-

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tance. The studies of interphase heat transfer in pneumatic conveying carried out up to now, are few and do not include the practically important range of higher concentrations of solid phase per unit of duct volume, viz. $\beta_v > 0{,}00035\ [m^3/m^3]$ and higher values of particle Reynolds number, viz.

$$2000 > Re_p = \frac{(U_g - U_s)\cdot d_p}{\nu} > 200$$

Investigations of interphase heat transfer between gas and solid particles can be distinctly divided into two topics: heat transfer to stationary particles and heat transfer to particles suspended in the flowing gas stream.

There is a disagreement as to the possibility of applying the results obtained in the studies of heat transfer from gas to stationary particles to the case of suspensions of the type occuring in pneumatic conveying. Differences of opinion in this matter result from essential differences in the views taken by the authors concerning the interaction between gas and stationary particles on the one side and between gas and particles suspended in the flowing gas stream on the other side. A synopsis of correlations describing heat transfer to stationary particles in the gas stream is represented in Fig. 1. The individual relationships are in comparatively good agreement in the range of Reynolds numbers $100 < Re_p < 10000$. Zenz and Othmer [15] recommend the use of the relationship of Kramers [6] derived from tests over a wide range of Reynolds and Prandtl numbers. On the other hand, Kunii and Levenspiel [16] suggest the correlation of Frössling [1], expressing the opinion that it may also be applied to systems with suspended particles. Observation of local values of heat transfer coefficient over a sphere's surface [9, 17] indicates that there are essential differences in the mechanisms of heat transfer in the front zone, in the boundary layer separation zone and in the rear zone. The increasing contribution of the turbulent boundary layer on the surface of the sphere (in the region of boundary layer separation) enables one to seek the solution for heat transfer coefficient in an equation of the form

$$Nu = A_1 . Re_p^{0,5} + B_1 . Re_p^{0,8} \qquad (1)$$

in which the individual terms correspond to the contribution of laminar and turbulent boundary layer respectively [8].

In Fig. 2 relationships are presented describing heat transfer from air to the particles moving in the gas stream. For the sake of comparison, Kramer's correlation [6] which pertains to heat transfer from air to a stationary sphere has also been included. A pronounced difference can be observed in the course of lines for both type of systems. According to

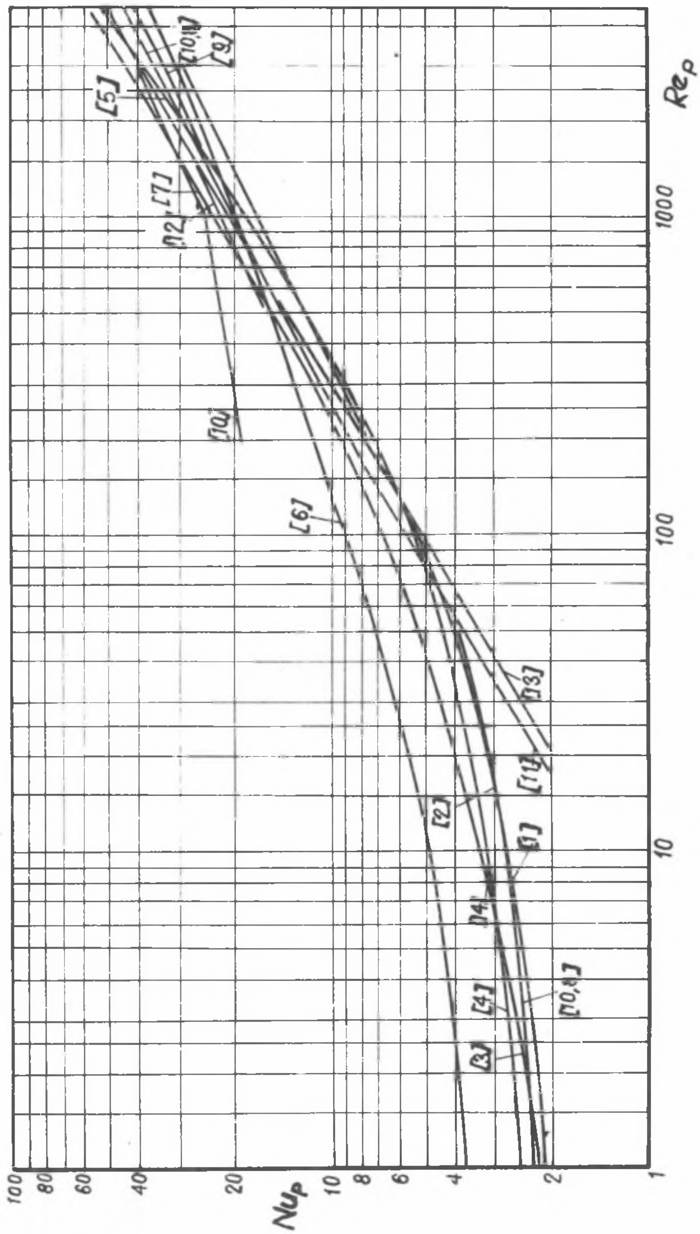

Fig. 1. Comparison of relationships $Nu_p = f(Re_p)$ for gas-stationary particle heat transfer

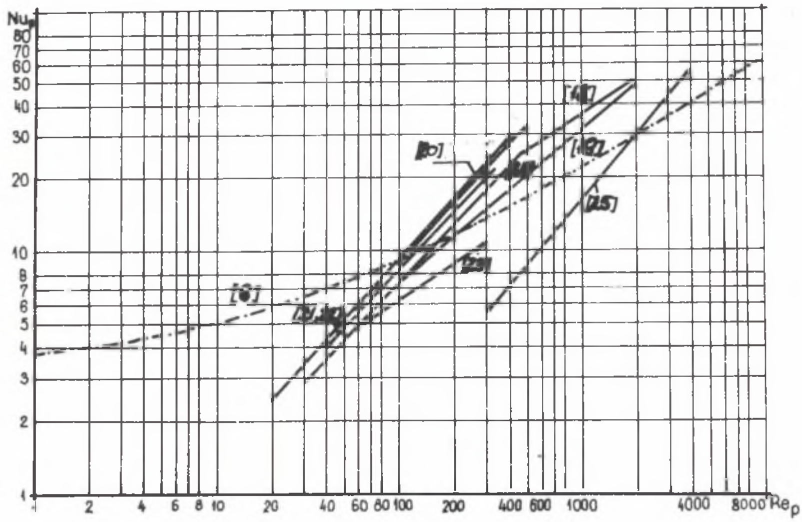

Fig. 2. Comparison of relationships $Nu_p = f(Re_p)$ for gas-particle heat transfer in gas-solid suspension

Chukhanov [28] and Gorbis [18] the rotation of particles in the gas stream accounts for the destruction of the relatively stable laminar boundary layer, this process taking place on an area larger that in the case of stationary particles. The predominating contribution of the turbulent boundary layer on the surface of the particle makes it possible to represent the heat transfer to suspended particles by means of an aquation of the form

$$Nu = A_o.Re_p^{0,82} \quad (2)$$

The lines represented in Fig. 2 are characterized by Reynolds number exponents close to 0,8, the discrepancies, however, between the values obtained from individual relationships, are considerable.The relations presented in Fig. 2 have been obtained for suspensions with volumetric concentration of the solid phase $\beta_v < 0{,}00035$.

The heat transfer data for gaseous suspensions of higher solid-phase concentration are limited; they comprise the very narrow range of concentrations ($\beta_v < 0{,}0025$) and Reynolds numbers ($Re_p < 330$). The corresponding relationships are given in Fig. 3. One can observe essential differences in the values of constant and exponent. Moreover, these results are based on the investigation of both upward pneumatic conveying of granular materials [19, 20] and the downward one [18, 21] as well of a bed of particles falling countercurrently to the gas stream [19].

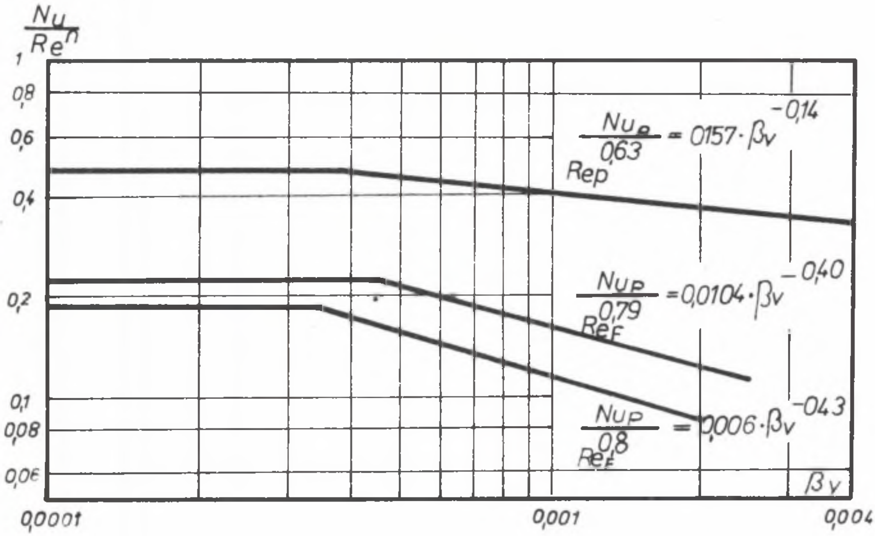

Fig. 3. Comparison of relationships allowing for the effect of concentration of solid particles in gas-solid suspension on interphase heat transfer

The gaseous suspensions practically encountered in pneumatic conveying are characterized by much higher volumetric solid-phase concentrations, $\beta_v < 0{,}05$, and the particle size corresponds to the transition range of flow ($200 < Re_p < 2000$).

For the pneumatic conveying corresponding to this region there is a lack of any information concerning gas-to-particle heat transfer.

Besides, the motion of particles in the gas stream is of an unsteady - state character with a large initial acceleration. The character of this motion affects, undoubtedly, the heat transfer process. This fact, however, has not been raised in the literature concerning the subject.

2. Experimental

The experimental system employs a closed circulation of granular material and open circulation of air. The apparatus is represented schematically in Fig. 4.

In this system the air, transported by fan 9 passes through the control valve 12, orifice meter 10 and electric heater 11 to the first section of the test tube 1, in which it heats the granular material fed to the bottom of the tube. The granular material is delivered to the feeder 7 from the cooler 5 through the control gate valve 13 and solids feed tank 6. After being heated, the granular material is separated from the air stream in the settling chamber 2 and cyclone 3 and next delivered to the fluidized-bed cooler 5. The material is directly cooled by contact with the cold air fluidizing the bed, as well as with the immersed water cooled heat exchange tube.

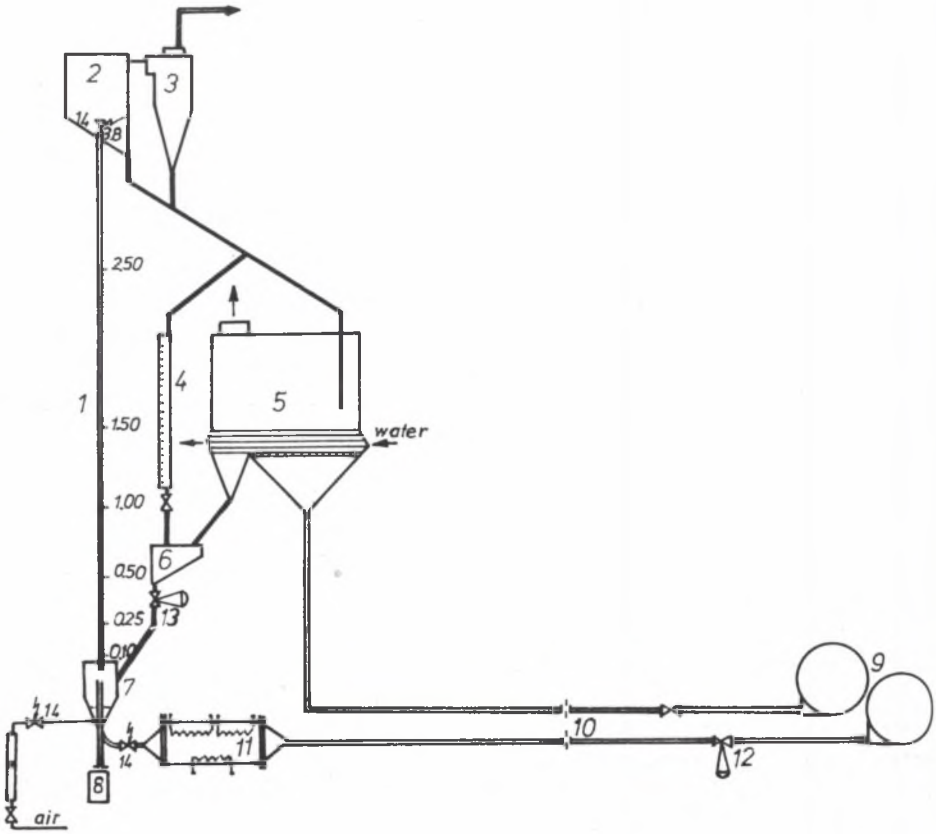

Fig. 4. Schema of experimental plant

The principal element of the apparatus is the vertical test tube 6×10^{-2} [m] i.d., equipped with electrical compensatory heating and with temperature and pressure probes fixed at levels 0,1, 0,25, 0.5, 1,0, 1,5, 2,5 and 3,8 [m], above the feed point of the granular material.

The air temperature along the height of the test tube has been measured by means of aspiratory thermoelements. The rate of air flow around the Cu-constantan junction was equal to $2{,}5\times10^{-4}$ [m^3/sec], ensuring this way a negligibly small error in the temperature measurement with the probe of small thermal inertia.

The temperature of the granular material before the feeder in the setting chamber has been measured calorimetrically.

The rate of flow of the material has been measured periodically after directing the material stream to the graduated cylinder 4, instead to the cooler 5.

Measurements were made after the system attained thermal equilibrium and the indication of thermocouples had been maintained at a constant level for at least 15 min and when temperature gradients across the thermal insulation of the test tube (between its outer wall and electrically heated screen made of sheet zinc) had been eliminated.

The granular material used in the experiments comprised ceramic spheres of 0,7, 1,33, 1,56, 1,83, 2,09 and 2,56 [mm] dia. and of density 2469 $[kg/m^3]$. The mean specific heat of this ceramic material and its thermal conductivity were 0,8 [kJ/ kg.K] and 2,1 [W/ m.K] respectively.

3. Analysis of results

Before proceeding with the experimental study of gas-to-particle heat transfer it was necessary to select an adequate model of the particle motion in the gas stream. This follows from the fact that the known methods of the measurement of granular material concentration (which quantity is needed for the calculation of heat transfer surface area) are unsuitable in simultaneous heat transfer experiments because they disturb the thermal equilibrium of the experimental apparatus to too large an extent.

Detailed analysis of the various models of motion of particle in a gas stream proposed by Gorbis [18], Khudyakov [27], Yang [28] and by Capes and Nakamura [29], as well as of the equation of motion of a single particle suspended in a gas stream, has shown [30] that-after some transformations - the individual equations can be reduced to a common relationship

$$\frac{du_s}{d\tau} = \frac{\rho_s - \rho_g}{\rho_s} \cdot g \cdot \left[\left(\frac{U_g - u_s}{U_u}\right)^E \cdot A_2 - B_2\right] \tag{3}$$

in which the exponent E and quantities A_2 and B_2 assume various values or forms, depending on the assumptions made by the authors in deriving the individual models. The Capes-Nakamura annular model of pneumatic conveying 30 gave a positive result in the verification of models.

This model has therefore been applied to the calculation of interfacial area and of particle Reynolds numbers in the heat transfer studies. The gas-to-particle heat transfer coefficient was then determined by making use of measured air temperature distributions obtained as described below, and of the known terminal temperature of the granular material.

Because of the time spread of the temperature readings at the individual levels of the test tube, it has proved to be of advantage in the interpretation of thermal measurements to use air temperature values calculated from temperature distributions fitted to the experimental values. Best results were obtained, using the fitting function

$$Y = \frac{t_{go} - t_g(H)}{t_{go}(H) - t_{mo}} = A_3 \cdot H^{B_3} \tag{4}$$

where t_{go} and $t_g(H)$ refer to the inlet air temperature, (for $H = 0$) and the air temperature at the height H respectively, t_{mo} is the mean stream temperature (for $H \to \infty$) calculated as

$$t_{mo} = \frac{G_s \cdot c_s \cdot t_{so} + G_s \cdot c_{pg}\Big|_0^{t_{go}} \cdot t_{go}}{G_s \cdot c_s + G_g \cdot c_{pg}\Big|_0^{t_{go}}} \tag{4a}$$

where t_{so} denotes the inlet temperature of solid particles.

The values of the constant A_3 and of the exponent B_3 were determined by the least-squares method.

Determination of the heat transfer coefficient was based on heat balances over successive 0,1 m sections of the test tube starting from the tube exit.

For such a section of the test tube, the following equation of heat balance may be written, assuming no heat losses:

$$-\Delta Q_g = \Delta Q_s \tag{5}$$

where

$$\Delta Q_g = G_g \cdot (C_{pg}\Big|_0^{t_{g1}} \cdot t_{gr} - C_{pg}\Big|_0^{t_{g2}} \cdot t_{g2})$$

$$\Delta Q_s = G_s \cdot (c_s\Big|_0^{t_{s1}} \cdot t_{s1} - c_s\Big|_0^{t_{s2}} \cdot t_{s2}) = G_s \cdot c_s(t_{s1} - t_{s2})$$

Hence

$$t_{s2} = t_{s1} - \frac{\Delta Q_g}{G_s \cdot c_s} \tag{6}$$

The overall heat transfer coefficient can be determined from the relation

$$k = \frac{\Delta Q_g}{\Delta A \cdot \Delta t_m} \tag{7}$$

In the case of these investigations the resistance to heat conduction inside the particle could be neglected, so that the overal heat transfer coefficient determined according to (7) was nearly exactly equal to the gas-to-particle heat transfer coefficient α. The mean temperature difference between the gas phase and the solid one has been calculated as logarithmic mean

$$\Delta t_m = \frac{(t_{g1} - t_{s1}) - (t_{g2} - t_{s2})}{\ln \frac{(t_{g1} - t_{s1})}{(t_{g2} - t_{s2})}} \tag{8}$$

The heat transfer surface area, in the tube element of the height ΔH, has been determined from

$$\Delta A = \frac{6 \cdot \beta_{V,loc}}{d_p} \cdot \Delta V = \frac{6 \cdot \beta_{V,loc}}{d_p} \cdot \frac{\pi D^2}{4} \cdot \Delta H \tag{9}$$

where $\beta_{V,loc}$ is given by eqn

$$\beta_{V,loc} = \frac{4 \cdot G_s}{\rho_s \cdot \pi \cdot D^2 \cdot u_s}$$

$$\Delta A = \frac{6 \cdot G_s}{\rho_s \cdot d_p \cdot u_s} \cdot \Delta H \tag{10}$$

Each value of the local velocity, u_s has been calculated at the mean gas temperature from the Capes-Nakamura annular model mentioned above.

The tabulated experimental results for all fractions of the granular material [31, 32] indicate the necessity of taking into account the effect of the character of motion of solid particles upon heat transfer coefficient α. In this connection one has decided to introduce and additional parameter X, defined as

$$X = \frac{U_g - u_s}{U_u} \tag{11}$$

This parameter appears also in the realtionship (3).

The analysis of the differential equation of heat transfer in the stream of a gaseous suspension of granular material, carried out by Gorbis [18], enables one to seek the solution for interphase heat transfer coefficient for a definite range of X, in a relationship of the form

$$Nu_p = \varphi(Re_p, Pr, \mu, \rho_s/\rho_g, D/D_p, B_i) \tag{12}$$

Taking into account that

$$\beta_{V,loc} = \mu \cdot \frac{\rho_s \cdot u_s}{\rho_g \cdot U_g} \tag{13}$$

and disregarding the effect of the group D/d_p [18] as well as the resistance to the heat conduction inside the particle, one can reduce the relationship (12) for a given system (Pr = const) to the form

$$N_{up} = \varphi'(Re_p, \beta_{V,loc}) \tag{14}$$

In further consideration a power form of the function was assumed

$$Nu_p = A_4 \cdot \beta_{V,loc}^{B_4} \cdot Re_p^{C} \tag{15}$$

and the values of the constant A_4 and of the power exponents B_4 and C were determined by the method of least squares.
The corresponding correlations are fo the form:

a) for X = 1 (steady - state motion of particles. In this case $u_s \approx U_s$ and $\beta_{V,loc} \approx \beta_V$)

$$Nu_p = 0{,}00114 \cdot \beta_V^{-0{,}5984} \cdot Re_p^{0{,}8159} \tag{16}$$

$0{,}00025 < \beta_V < 0{,}05$ and $180 < Re_p < 1860$
Mean error: 14,9%

b) for $1 < X \leqslant 1{,}5$

$$Nu_p = 0{,}0054 \cdot \beta_{V,loc}^{-0{,}5782} \cdot Re_p^{0{,}6324} \tag{17}$$

$0{,}00025 < \beta_{V,loc} < 0{,}009$ and $240 < Re_p < 2360$
Mean error: 14,8%

c) for $1{,}5 < X \leqslant 2$

$$Nu_p = 0{,}0075 \cdot \beta_{V,loc}^{-0{,}5966} \cdot Re_p^{0{,}5764} \tag{18}$$

$0{,}00028 < \beta_{V,loc} < 0{,}013$ and $240 < Re_p < 2440$
Mean error: 16,3%,

As may be seen, the values of constants in Eqs (17) and (18) as well as exponents at Re_p tend, as X diminishes from 2 to 1, towards values obtained for X = 1 (cf. Eq (16)).

The values of the constant and of the exponent may be connected with the character of motion of particles along the height of the tube, since - practically - the only variable in all the cases considered is the parameter X. The exponent at the volumetric concentration of the material remains practically constant. Making use of Fig. 2, which indicates that the exponent at Re_p assumes the lowest value of 0,5 (which is valid, approximately, also for own investigations for $X \to 2$) and is equal to ca 0,8 for X = 1, one obtains the following relationships:

a) for the exponent

$$C = 0{,}8159 - 0{,}3159 \cdot \sqrt{1-1/X} \tag{19}$$

b) for the constant

$$A_4 = 0{,}00114 + 0{,}0094 \cdot \sqrt{1-1/X} \tag{20}$$

The values of C and A_4, as functions of X, are presented in Fig. 5 and 6, correspondingly.

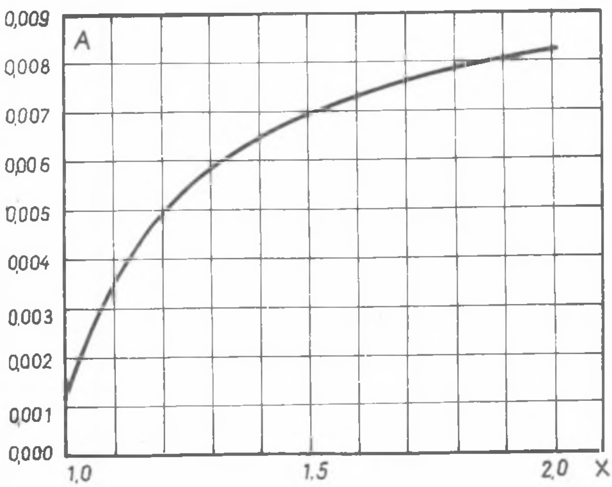

Fig. 5. Value of constant A_4 in equation $Nu_p = A_4 \cdot \beta_v^B \cdot Re_p^C$ in dependence on X

. The proposed forms of the functions C = F(X) and A_4 = f(X) have been chosen from among a few tested ones, as characterized by the smallest error.

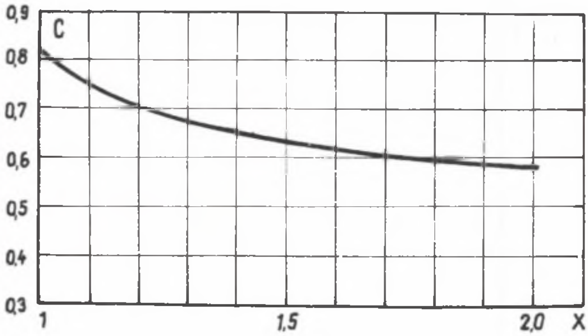

Fig. 6. Value of exponent C in equation $Nu_p = A_4 \cdot \beta_v^B \cdot Re_p^C$ in dependence on X

One may also assume, in view of an unsignificant difference between the values of exponents at β_v in individual ranges of X, the mean value of this exponent, equal to -0,5911.

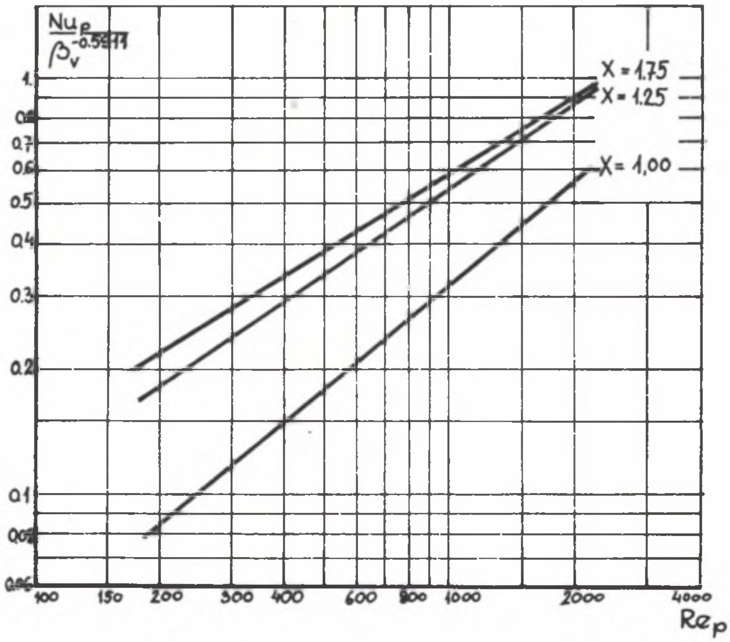

Fig. 7. Course of correlation (21) in coordinates $\log(Nu_p/\beta_v^B)$ - log Re_p for X = 1; 1,25; 1,75

So, the general form of the relationship for gas-to-particle heat transfer coefficient is as follows:

$$Nu_p = A_4 \cdot \beta_V^{-0,5911} \cdot Re_p^C \tag{21}$$

where A_4 is given by Eq (20), C - by Eq (19) and X - by Eq (11). This relationship is walid in the range $1 \leqslant X \leqslant 2$; $0,00025 < \beta_V < 0,05$; and $180 < Re_p < 2440$. The obtained correlation is represented in Fig. 7.

Notation

A - area
A_1, B_1 - eqn (1)
A_2, B_2, E - eqn (3)
A_3, B_3 - eqn (4)
A_4, B_4, C - eqn (15)
Bi - Biot number, $\frac{\alpha d_p}{\lambda_s}$
c - specific heat
d - particle diameter
D - test tube diameter
g - acceleration due to gravity
G - rate of flow
H - tube height
k - overall heat transfer coefficient
Nu - Nusselt number $\frac{\alpha d_p}{\lambda_g}$
Q - heat transferred
Re_p - particle Reynolds number
t - temperature
Δt_m - logarithmic mean temperature difference
U - velocity
U_u - terminal particle velocity
u - local velocity
V - test tube volume
x - random variable, eqn (7)

Greek symbols

α - gas-to-particle heat transfer coefficient
β_V - volumetric concentration of granular material in the tube
Δ - difference operator
λ - thermal conductivity
μ - G_s/G_g, solid-gas ratio

ρ - density
τ - time
ψ - shape factor

Subscripts

g - gas
loc - local
s - solid
1,2 - inlet and outlet conditions (in heat balance)

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WSPÓŁCZYNNIK WNIKANIA CIEPŁA OD GAZU DO CIAŁA STAŁEGO W PIONOWYM TRANSPORCIE PNEUMATYCZNYM W OBSZARZE NIEUSTALONEGO RUCHU CZĄSTEK

S t r e s z c z e n i e

Wyniki badań wymiany ciepła w pionowym transporcie pneumatycznym w obszarze ustalonego i nieustalonego ruchu cząstek pozwoliły na opracowanie korelacji opisującej wnikanie ciepła od gazu do cząstek ciała stałego danej zależnością

$$\overline{Nu}_p = A \cdot \beta_v^{-0,5911} \cdot Re_p^C,$$

gdzie:

$$A = 0,0014 + 0,0094\sqrt{1 - \frac{1}{X}},$$

$$C = 0,8159 - 0,3159\sqrt{1 - \frac{1}{X}},$$

$$X = \frac{U_g - u_s}{U_u},$$

słusznej dla $180 < Re_p < 2440$; $2,5 \cdot 10^{-4} < \beta_\epsilon < 0,05$; $1 \leqslant X \leqslant 2$.

Uzyskana zależność sprowadza się, dla $X = 1$, do otrzymanej uprzednio zależności obowiązującej w obszarze ustalonego ruchu cząstek.

КОЭФФИЦИЕНТ ТЕПЛООТДАЧИ ОТ ГАЗА К ТВЁРДОМУ ТЕЛУ В ВЕРТИКАЛЬНОМ ПНЕВМОТРАНСПОРТЕ В ОБЛАСТИ НЕУСТАНОВИВШЕГОСЯ ДВИЖЕНИЯ ЧАСТИЦ

Р е з ю м е

Результаты исследований межфазного теплообмена в вертикальном пневмотранспорте в области установившегося и неустановившегося движения частиц позволили разработать корреляцию, описывающую теплоотдачу от газа к твёрдым частицам, согласно уравнению

$$Nu_p = A\,\beta_v^{-0,5911} \cdot Re_p^{C}$$

$$A = 0,00114 + 0,0094\sqrt{1 - \frac{1}{X}}$$

$$C = 0,8159 - 0,3159\sqrt{1 - \frac{}{X}}$$

$$X = \frac{U_g - u_s}{U_s}$$

справедливому для $180 < Re_p < 2440$; $2,5 \cdot 10^{-4} < \beta_v < 5.10^{-2}$, $1 \leqslant X \leqslant 2$. Полученная корреляция сводится, для $X = 1$, к прежне полученной зависимости, справедливой в области уотансвившегоося движения частиц.