HEAT EXCHANGE OF A SWIRLED STREAM OF A GAS SUSPENSION IN A PIPE

Yu. Ya. Pechenegov

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The results of an experimental investigation of heat exchange during turbulent flow of a gas containing suspended particles of a solid material in a horizontal pipe are presented.

Heat exchange during the flow of a swirled stream of gas suspension in a pipe still remains little studied, although for one-phase flows swirling is widely used to intensify heat transfer [1]. A well-known paper is [2], where the influence of a twisted ribbon placed in a pipe (such a device is used most appropriately for stream swirling under industrial conditions [1]) on the heat exchange of a gas suspension was investigated. The relative pitch of twisting of the ribbon was s/D = 7.5, while the graphite particles used as the solid phase of the stream had sizes of 1-5 μm. Because of their low inertia, such particles are entrained relatively easily by turbulent pulsations of the carrier gas medium [3]. According to the data of [2], the ribbons used permit considerable intensification of heat exchange.

It is interesting to study the characteristics of heat exchange for less swirling (s/D > 7.5) of a stream of gas suspension containing larger particles of the solid phase, which are not entrained by turbulent vortices but interact with the averaged gas flow. The different degrees of inertia of small and large particles can result in differences in the formation of the structure of streams of gas suspension, and hence they can affect the heat exchange.

The results of an experimental investigation of heat exchange of a swirled stream of gas suspension in a horizontal pipe 0.014 m in diameter are given in the present paper.

A detailed description of the experimental setup, the test procedure, and the measurement technique is given in [4]. The path of motion of the heat-transfer agent was open for both phases. Sectioned external warming of the measurement section with radiant electric ovens permitted regulation of the wall-temperature distribution within sufficiently broad limits, and the heat-exchange characteristics for different pipe lengths, x = 1, 2, 3, and 4 m, were found in each test. The heated section preceded the adiabatic section of acceleration of solid particles, 0.75 m in length.

Air served as the carrier medium in the tests, while two fractions of marble particles 100-250 and 250-500 μm in size were used as the solid phase. The flow-rate concentration of particles was varied from 0.1 to 7 kg/kg air, while the Reynolds number of the gas was Re_{w,D_e} = 1900-7000. The stream temperature at the entrance to the heated section was 25-40°C. The wall temperature was kept approximately constant along the pipe length in each test and lay in the range of 200-600°C. The particle transportation was stable in all the tests and pressure pulsations were not observed in the stream.

Technically smooth ribbon of stainless steel, $0.25 \cdot 10^{-3}$ m thick and 0.0135 m wide, which was mounted along the entire length of the heated section, was used for swirling the stream. The flow was investigated for the following relative pitches of ribbon twisting: S/D = ∞ (straight ribbon); 28.6; 19; 13.6. In all cases, in the initial cross-section of the measurement section, the leading edge of the ribbon was set vertically in the diametral plane of the pipe. The ribbon was fixed spatially by rigid attachment at the end of the pipe and stretching from a thin wire at the start.

In the tests with a gas suspension, the heat-exchange coefficient was determined from the formula

$$\alpha = \frac{Q}{\pi D x\,(t_w - t_0)} \tag{1}$$

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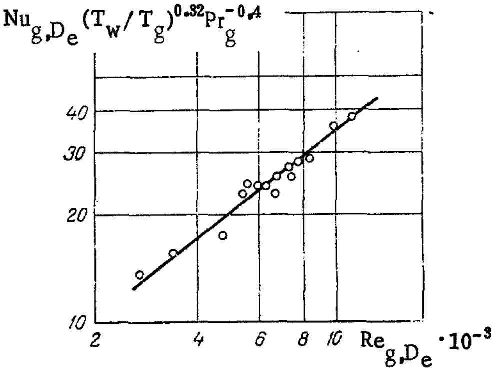

Fig. 1. Heat exchange for air flow in a pipe with a straight ribbon: $x = 1$ m, $x/D_e = 118.8$.

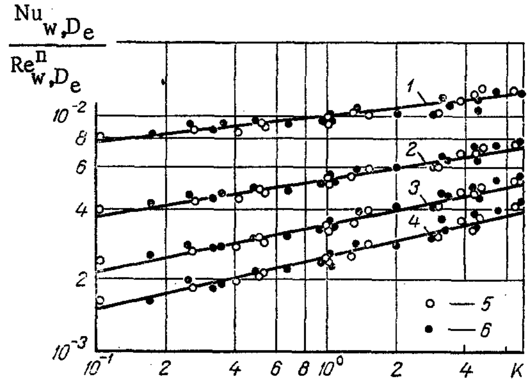

Fig. 2. Heat exchange in the flow of a gas suspension in a pipe with a twisted ribbon; $s/D = 19$: $x = 1$ m; 2) 2; 3) 3; 4) 4 m; 5) $d_p = 175$ μm; 6) 375 μm; lines correspond to Eq. (3).

with a limiting relative error of 6%. The value of Q in (1) was found from the difference in the amounts of power supplied and lost over the length x of the pipe section. We note that it consists of the sum of the amounts of thermal power taken by the stream from the pipe wall and from the surface of the ribbon. The latter component is due to the internal-fin effect and radiative heat transfer in the pipe-wall–plate system. It is difficult to determine this component exactly. Its relative value is usually small [5], however, and was estimated not to exceed 10% of Q for the conditions of our tests. Therefore, the heat-exchange coefficient based on (1) characterizes the intensity of the process at the pipe wall almost completely.

In the initial series of tests, we measured heat exchange in the flow of pure air in a pipe with a straight ribbon. For the comparison with the data of other authors, in these tests the heat-exchange coefficient was calculated from the logarithmic-mean temperature difference, with the initial temperature t_0 of the stream being measured while the final temperature was calculated from the heat balance over the section.

The results of the measurements are presented in Fig. 1. Here the average air temperature and the equivalent diameter of the channel are the determining quantities in the Nusselt and Reynolds numbers. The straight line in the figure corresponds to the equation

$$\mathrm{Nu}_{g,D_e} = 0{,}021\,\mathrm{Re}_{g,D_e}^{0,8}\,\mathrm{Pr}_g^{0,4}\,(T_g/T_w)^{0,32}, \tag{2}$$

which generalizes the experimental data of [5], obtained for the case of air flow in a pipe with a straight ribbon under high heat loads. We can state that our results (a value of $T_w/T_g = 1.81$ was reached in the tests) is in good agreement with the data of [5].

The test results on heat exchange for a gas suspension are presented in Figs. 2 and 3. It is seen from Fig. 2 that the heat-exchange intensity is the same for the fractions of solid particles used, with average sizes $d_p = 175$ and 375 μm. The same result was obtained for other values of the parameter s/D. It is seen that the influence of the flow-rate concentration of the solid phase on the heat exchange becomes more pronounced with an increase in pipe length.

The experimental data obtained were approximated by the function

$$\mathrm{Nu}_{w,D_e} = \left[1 + \exp\left(-\,0{,}095\,\frac{s}{D}\right)\right]\frac{D_e}{x}\,\mathrm{Re}_{w,D_e}^{n}\,K^m, \tag{3}$$

where $n = 0.526\,(x/D_e)^{0.081}$; $m = 0.015\,(x/D_e)^{0.44}$. The scatter of the test points, when they are generalized by the function (3), does not exceed 10% (Fig. 3). The vertical lines on the symbols in Fig. 3 show the ranges of variation of the complex Ko for x = 1-4 m.

Let us compare the intensities of heat exchange during the flow of a gas suspension in pipes with and without a ribbon. The heat-exchange equation for the latter case was derived in [6]. The use of this equation and the function (3) allows us to write for the relative heat-exchange coefficient

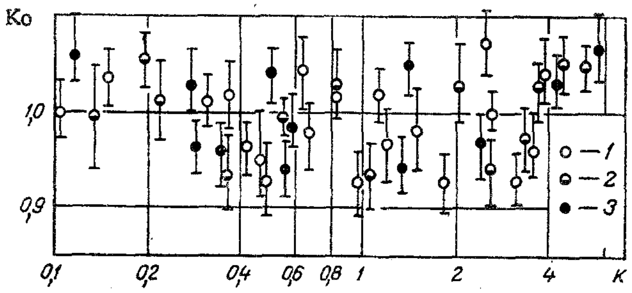

Fig. 3. Generalization of test data on heat exchange for a gas suspension; $Ko = Nu_{w,D_e}/\{[1 + \exp(-0.095s/D)](D_e/x)Re^{n}_{w,D_e}k^{m}\}$: 1) $s/D = \infty$; 2) 28.6; 3) 13.6.

$$\tilde{\alpha} = \frac{\alpha_w}{\alpha_{str}}\bigg|_{T_w=\mathrm{idem}} = 2{,}1\left(\frac{D}{x}\right)^{0{,}11}\left[1+\exp\left(-0{,}095\,\frac{s}{D}\right)\right]\times\left(\frac{D_e}{D}\right)^{n}\frac{K^m}{1+0{,}3K}\,Re^{c}_{w,D_e}, \tag{4}$$

where $c = n - 9.526\,(x/D)^{0.081}$. Here the exponent c is very small ($c \leq 0.04$), so that the variation of the Reynolds number in the range occurring in the tests hardly affects the value of $\tilde{\alpha}$.

From Fig. 4, illustrating the influence of various parameters on the relative heat exchange, it is seen that the heat exchange itensifies with a decrease in s/D. The fact that for zero stream swirling (a straight ribbon, D/s = 0), the heat-exchange intensity decreases in comparison with the case of flow in a pipe without a ribbon attracts attention. This decrease is the more pronounced, the larger K and x. This situation results in the fact that the value of $\tilde{\alpha}$ remains less than unity even for stream swirling with s/D = 13.5 if K > 1 while x = 4 m.

The function (4), extrapolated to the experimental conditions of [2], yields a value of $\tilde{\alpha}$ about 20% lower than that obtained in [2] for K = 1. The discrepancy grows with an increase in K, since in this case, according to the data of [2], the ratio α_{sw}/α_{str} grows little, in contrast to our results.

The complexity and lack of study of the internal physical connections and fluid-mechanical characteristics of the flow of a gas suspension hinder the interpretation of the results obtained. We can assume, however, that the decrease in heat-exchange intensity when a straight ribbon is placed inside the pipe is due mainly to the decrease in the role of radial particle movements in heat transfer, since the presence of the ribbon limits such movement.

The swirling of the stream inevitably results in a redistribution of the true particle concentration in a channel cross-section and to their concentration predominantly in the wall zone. Growth of K increases the local concentration of solid particles near the wall. It also grows along the length of the pipe, since the separating capacity of the stream increases together with the gas velocity as it is heated. It is well known that even with strong stream swirling, the particles move not along the wall surface but in jumps near it, creating a kind of boundary layer.

This layer of particles screens the wall, as it were, and it retards, to a certain extent, the exchange processes between the wall and central zones of the stream, being a barrier to the development of secondary flows and nucleation and to the propagation of pulsations of the gaseous medium. On the other hand, the increased particle concentration in the wall zone promotes an increase in their direct interaction with the wall and the viscous gas sublayer, which should result in the intensification of heat exchange.

It is obvious that one or the other of these factors will come to dominate under different flow conditions. We can assume that the role of these factors in the mechanism of heat transfer in streams containing large particles is essential, and their simultaneous and oppositely directed influence on the heat-exchange intensity determine and explain its characteristics to a considerable extent.

In the swirled stream of gas suspension of [2], the action of centrifugal force on the particles is neutralized to a certain extent by their turbulent diffusion. The wall layer

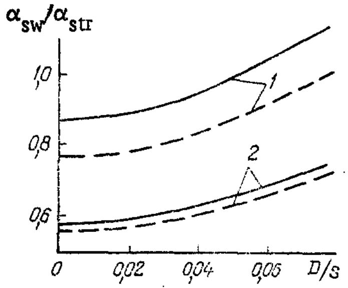

Fig. 4. Variation of α_{sw}/α_{str} as a function of D/s: 1) K = 1; 2) 5; solid curves) x = 1 m; dashed curves) 4 m.

with an increased particle concentration is far less strongly expressed, while the particles themselves continue to transfer heat actively in the radial direction. Therefore, the heat-exchange intensity can be higher here than for streams containing larger particles, and this also follows from the above comparison of the results of the present work with the data of [2].

NOTATION

D, pipe diameter; x, length of pipe section; s, pitch of ribbon twisting, corresponding to turning of the ribbon through 360°; $D_e = D(\pi D - 4\delta)/[\pi D + 2(D - \delta)]$, equivalent diameter of the channel; δ, ribbon thickness; d_p, particle diameter; $K = G_p/G$, flow-rate concentration of solid particles; G_p and G, mass flow rates of particles and gas; Q, heat-flux power in the section; α, heat-exchange coefficient; T and t, temperature. Similarity numbers: Nu, Nusselt; Re, Reynolds; Pr, Prandtl. Indices: w, wall; 0, entrance to the measurement section; g, average gas temperature; sw, swirled stream; str, stream in a pipe without a ribbon.

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