UNSTEADY CONVECTIVE HEAT TRANSFER IN THE HEATING OF A LIQUID IN A PIPE BY A VARIABLE HEAT FLUX

G. A. Dreitser, V. D. Evdokimov,
and É. K. Kalinin

UDC 536.244

We present the results of an experimental study and a generalization of experimental data on unsteady heat transfer in the turbulent flow of a liquid in a pipe and the time dependence of the heat flux at the wall.

Studies of unsteady heat-transfer processes in channels performed by heating and cooling gases [1] showed that the difference between the unsteady heat-transfer coefficient and its quasisteady value is critically dependent on the thermal and hydrodynamic unsteadiness criteria, the Reynolds number, and the temperature factor. Analysis of the experimental results [2,3] and a comparison of them with numerical calculations for a quasisteady distribution of the turbulence structure showed that the substantial difference between K and unity is not determined by a superposition of unsteady heat conduction on convective heat transfer, but by a change of the turbulent flow structure. The unsteady character of the temperature boundary conditions $\partial t_w/\partial\tau$ plays a basic role in this and is best taken into account, as shown in [3,4], by the criterion

$$K_{Tg}^{*}=\frac{\partial t_{w}}{\partial \tau}\,\beta d\sqrt{\frac{\lambda}{c_{p}gG}}\,. \tag{1}$$

On the basis of the experiments performed, empirical generalized relations were obtained for unsteady heat transfer in the heating and cooling of gases and for various laws of variation of the wall temperature and the gas flow rate.

The existing experimental data on unsteady heat transfer in the flow of fluids in channels [5] are incomplete and do not permit the determination of the effect of the Re and Pr numbers.

We present results of an experimental investigation of the unsteady heat-transfer coefficient in the turbulent flow of water in a circular pipe of 1Kh18N10 steel with an inside diameter of 8.63 mm, a wall thickness of 0.183 mm, and a length of 1510 mm in the range $Re_b = 5\cdot10^3$–10^5; Pr_b = 2–12; and Pr_b/Pr_w = 1–3.7.

The pipe was heated by a low-voltage alternating electric current. Unsteady heat-transfer processes were investigated for a time-varying heat release in the pipe wall and a constant water flow rate. During the experiments measurements were made of the water flow rate with a diaphragm or normal nozzle and the inlet and outlet water temperatures and pressures with Chromel—Alumel thermocouples having thermoelectrodes 0.1 mm in diameter and DDI-21 inductive pressure transducers operating in an assembly with an ID-2I device, the current flowing through the experimental pipe and the potential drop occurring across eight parts of the pipe, the first length being 110 mm and the rest, 200 mm. The responses of all the transducers were exhibited on N010M and N700 oscillographs.

All the measuring systems for unsteady conditions were specially calibrated and monitored in each unsteady regime by steady-state regimes before and after the experiment. The time lag of all the transducers was estimated and ensured by accurate recording of parameters during unsteady regimes. The leakage of heat from the outside surface of the pipe was found by calibration experiments to be negligibly small (0.1-0.2% of the heat released).

Sergo Ordzhonikidze Moscow Aviation Institute. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 31, No.1, pp.5-12, July, 1976. Original article submitted February 18, 1975.

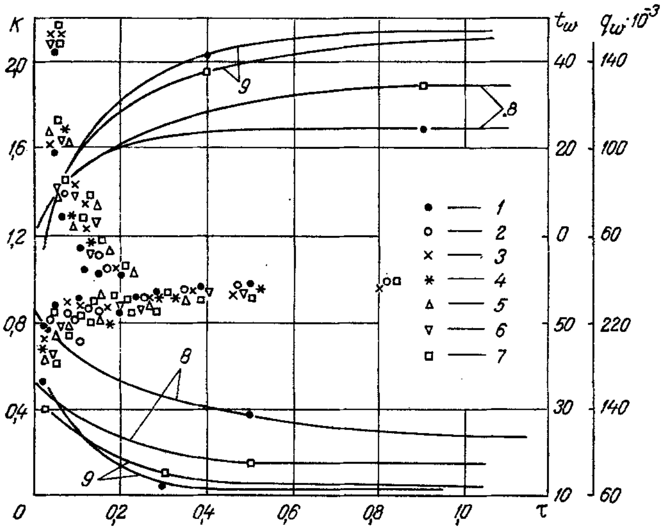

Fig. 1. Time dependence of wall temperature t_w (°C), heat flux density q_w (W/m²), and K during an increase [Re_b = (1-1.4)·10^4, Pr_b = 7-11, K > 1] and a decrease [Re_b = (1.2-2)·10^4, Pr_b = 6-9, K < 1] of the heat load: 1-7) x/d = 12.7, 36, 59, 82, 105, 128, and 151, respectively; 8) t_w; 9) q_w. τ (sec).

The unsteady temperature of the pipe wall was measured by a practically inertialess method based on the change of the electrical resistance of the pipe material with temperature. The highly sensitive circuit developed enabled us to obtain a linear relation between the signal fed to the oscillograph and the temperature. The maximum absolute error of a measurement of the unsteady temperature by this method depends on the maximum temperature drop during the unsteady process. Taking account of the errors in measuring steady temperatures and the calibrations, this error for the 10-20°C temperature drops occurring in the experiments was 0.2-0.3°C. The system was calibrated with 17 Chromel—Alumel thermocouples having 0.05-mm-diameter thermoelectrodes welded to the outer surface of the pipe. The measuring system is described in detail in [6].

The procedure for determining the unsteady heat-transfer coefficient

$$\alpha(x, \tau) = \frac{q_w(x, \tau)}{t_w(x, \tau) - t_b(x, \tau)} \tag{2}$$

is similar to the procedure used earlier in experiments on gases [1]. The quantities $q_w(x,\tau)$ and $t_w(x,\tau)$, necessary to determine $\alpha(x,\tau)$, were found from the solution of the inverse heat-conduction problem by measuring the average temperature over a cross section of the wall and the heat release in the pipe walls with the condition that the heat flux is zero at the outer surface of the pipe wall. The quantity $t_b(x,\tau)$ was found from the solution of the one-dimensional energy equation where, in contrast with the flow of gases, the residence time of the liquid in the pipe was taken into account. The heat-transfer coefficients were calculated for seven cross sections located at the boundaries of the eight sections of the pipe across which the potential drop was measured with x/d = 12.7, 36, 59, 82, 105, 128, and 151.

The experimental results were processed on a BÉSM-4 computer. The maximum relative error in the determination of the unsteady heat-transfer coefficient did not exceed 10-15%.

The value of Nu_0 was determined from the expression [7]

$$Nu_0 = 0.023\, Re_b^{0.8} Pr_b^{0.4} \left(\frac{Pr_b}{Pr_w}\right)^{0.11} \varepsilon_L, \tag{3}$$

where the correction ε_L to the initial section was taken from [8] for the hydrodynamic stabilization of the flow before the heat-transfer section:

$$\varepsilon_L = 1 + 0.5\frac{d}{x}. \tag{4}$$

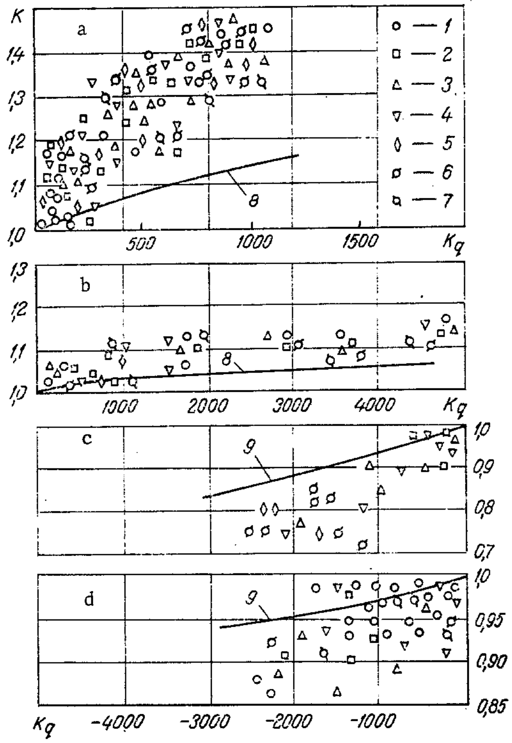

Fig. 2

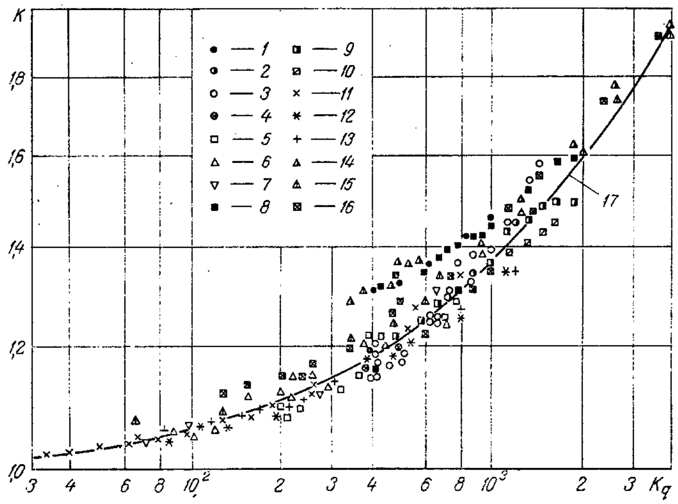

Fig. 3

Fig. 2. Dependence of K on K_q for various Re and Pr numbers: 1-7) x/d = 12.7, 36, 59, 82, 105, 128, and 151, respectively; 8, 9) calculated with (6) and (7); a, c) $Re_b = (7.5\text{-}10)\cdot 10^3$, $Pr_b = 8\text{-}12$; b) $Re_b = (5\text{-}7)\cdot 10^4$, $Pr_b = 4\text{-}6$; d) $Re_b = (3\text{-}4)\cdot 10^4$, $Pr_b = 6\text{-}8$.

Fig. 3. Dependence of unsteady heat-transfer data on K_q for various laws of variation of the heat flux density, calculated from data in [9] for Re = 10^4 and Pr = 1: 1-4) $q = A(e^{\alpha Fo} - 1)$; $\alpha = 100$; x/d = 1.58; 3.16; 7.80; 6.2-197 (X = Fo), respectively; 5-7) $q = A(e^{\alpha Fo} - 1)$; x/d = 7.86; α = 50, 10, 2; 8-10) $q = 0.1 + (e^{100 Fo} - 1)$; x/d = 1.58; 3.16; 7.86; 11-13) $q = AFo^m$, x/d = 22.2; m = 1, 2, 3, respectively; 14-16) q = sin 100Fo; x/d = 3.16; 31.6; 1.97-8.67 (X = Fo); 17) by Eq. (5).

Equation (3) satisfactorily describes the local heat-transfer data obtained in the range $Re_b = 3\cdot 10^3\text{-}6\cdot 10^4$ and $Pr_b = 2\text{-}11$ in preliminary experiments during steady regimes.

Unsteady processes produced by a stepwise increase or decrease of the heat release in the pipe walls were investigated. During an increase of the heat load the initial current was zero or approximately one quarter as large as the final value. During a decrease of the heat load the final current was one quarter as large as the initial. The basic parameters in these experiments were varied within the following limits: water pressure, p = 1-5 bar; water flow rate, G = 0.024-0.562 kg/sec; inlet water temperature, t_{b0} = 3.6-50°C; wall temperature, $t_w = t_{b0}$-107°C; power liberated in the working portion, 0-20.2 kW; heat flux density, q_w = 0-0.5 MW/m^2; $Re_b = 5\cdot 10^2\text{-}10^5$; $Pr_b = 2\text{-}12$; $Pr_b/Pr_w = 1\text{-}3.7$.

Typical curves of the time dependence of the basic parameters are given in Fig. 1. For a stepwise turning on of the electrical load the maximum rate of increase of the wall temperature at zero time reached a value $\partial t_w/\partial\tau$ = 560 deg/sec, and for turning off — 500 deg/sec. The corresponding values of K at zero time were, respectively, 1.6-2.2 and 0.5-0.7. As t_w was stabilized they approached 1. The residence time of water in the experimental section varied from 0.008 to 3.5 sec, and the stabilization time for the wall temperature varied from 0.1 to 6 sec. The stabilization time for the heat-transfer coefficient was approximately half as long as that for the wall temperature. The experiment did not show any difference in the dependence of K on τ for τ shorter than the time for the liquid to pass from the pipe inlet to the cross section under consideration, and for τ longer than this time.

To find the dependence of unsteady heat transfer on Pr_b, Re_b, and Pr_b/Pr_w all the experimental points were divided into several ranges of variation of these parameters. The following ranges were chosen: $Re_b\cdot 10^{-4}$ = 0.3-0.5; 0.5-0.75; 0.75-1; 1-1.5; 1.5-2; 2-3; 3-4; 4-5; 5-7; 7-8.5; 8.5-10; Pr_b = 2-4; 4-6; 6-8; 8-12; Pr_b/Pr_w = 1-2; 2-3.75. Figure 2 shows the dependence of K on the thermal unsteadiness criterion K_q for several ranges.

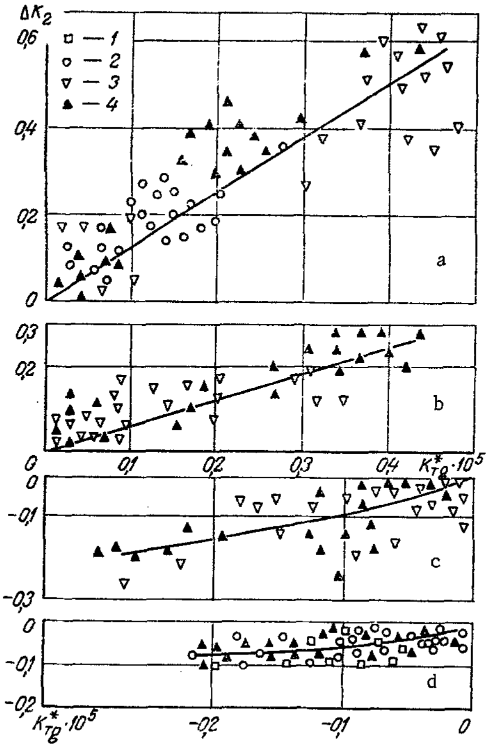

Fig. 4. Dependence of ΔK_2 on K^*_{Tg} for various Re_b and Pr_b during an increase [a, b) for $Re_b = (5\text{–}7.5)\cdot 10^3$ and $Re_b = (4\text{–}5)\cdot 10^4$, respectively] and a decrease [c, d) for $Re_b = (7.5\text{–}10)\cdot 10^3$ and $Re_b = (2\text{–}3)\cdot 10^4$] of the heat flow density: 1-4) Pr_b = 3-4, 4-6, 6-8, 8-12, respectively.

In the processing neither x/d nor Pr_b/Pr_w affects K. As can be seen from Fig. 2 the effect of K_q on K decreases with increasing Re_b. Measurements [5] performed over a narrower range of Re values showed a somewhat larger effect of thermal unsteadiness on K.

The experimental points obtained were compared with the results of theoretical calculations described in detail in [1]. These calculations were performed under the assumption that in an unsteady process the turbulent structure of the flow remains quasisteady and takes account of the effect of the temperature profile in the boundary layer on unsteady heat transfer. The difference between these profiles and quasisteady profiles is due to the unsteady heating or cooling of this layer; it increases as $|K_q|$ increases.

The relation taking account of the effect of unsteady heat conduction on K was obtained by using the results of calculations [9] performed for Re = 10^4 and Pr = 1 for the hydrodynamically stabilized flow of a liquid with constant properties. As can be seen from Fig. 3, for various laws of variation of the heat flux (except for the practically unimportant stepwise increase in the heat flux according to the law $q = A\,Fo^m$ for m = 0) the results of the calculation of $K = f(K_q)$ are satisfactorily generalized by the single relation

$$K = \frac{\mathrm{Nu}}{\mathrm{Nu}_0} = 1 + \Delta K_1 = 1 + 0.00266\, K_q^{0.71} \tag{5}$$

for K_q = 0-4000 and x/d = 3.16-197. Here Nu_0 is the quasisteady stabilized value of Nu. The dependence of ΔK_1 on Re and Pr was found by using the results of calculations [9] performed for various Re and Pr for $q = A\cdot Fo^m$. Here $K_q = m/Fo$; for Fo = const, K_q = const. For Fo = const the values of ΔK_1 for various Re and Re = 10^4 for Pr = 1, and for various Pr and Pr = 1 for Re = 10^4 were compared. The value of ΔK_1 decreases with increasing Re and Pr. The resulting generalized relation has the form

$$\Delta K_1 = \frac{26.6\,(K_q)^{0.71}}{\mathrm{Re}\cdot \mathrm{Pr}^{0.6}} \tag{6}$$

for Re = 10^4-10^6 and Pr = 1-10. Equation (6) was verified by calculations performed by the method of [10]. The dependence of ΔK_1 on K_q for a decreasing heat flux was calculated by this method and has the form

$$\Delta K_1 = \frac{1}{1 - \dfrac{2.4\, K_q}{\mathrm{Re}\cdot \mathrm{Pr}^{0.6}}} - 1 \tag{7}$$

for $K_q = -2\cdot 10^3$-0, Re = 10^4-10^5, and Pr = 1-10.

Equations (6) and (7) are compared with the experimental points in Fig. 2. The experimental data show a stronger influence of the thermal unsteadiness on the deviation of K from 1 than the results of the calculation which assumes quasisteady turbulence. For example, Fig. 2a shows that for $K_q = 1000$ the calculated value of K is 1.15, while for experiment K = 1.4–1.5.

Thus, in contrast with unsteady heat transfer for the flow of gases, the deviation of the unsteady heat-transfer coefficient from the quasisteady value in this case is due approximately equally to the superposition of unsteady heat conduction on steady convective heat transfer and the effect of unsteady boundary conditions on the turbulent structure of the flow. Therefore, the generalized relations for unsteady heat transfer during a change in the heat load at a constant flow rate of the liquid are obtained in the form

$$K = 1 + \Delta K_1 (K_q, \mathrm{Re}_b, \mathrm{Pr}_b) + \Delta K_2 (K^*_{Tg}, \mathrm{Re}_b), \tag{8}$$

where ΔK_1 is the calculated change in K as a result of unsteady heat conduction; ΔK_2 is the change in K due to the change in the turbulent structure of the flow, and depends on the corresponding criterion K^*_{Tg} given by Eq. (1). The value of ΔK_2 is found to be

$$\Delta K_2 (K^*_{Tg}, \mathrm{Re}_b) = K_e (K^*_{Tg}, \mathrm{Re}_b, \mathrm{Pr}_b, \mathrm{Pr}_b/\mathrm{Pr}_w) - 1 - \Delta K_1 (K_q, \mathrm{Re}_b, \mathrm{Pr}_b),$$

where K_e is the experimental value of K.

As is clear from Fig. 4, $\Delta K_1 > 0$ for $K^*_{Tg} > 0$ and $\Delta K_2 < 0$ for $K^*_{Tg} < 0$. For K^*_{Tg} = const, $|\Delta K_2|$ decreases with increasing Re_b. In the range of parameters investigated ΔK_2 does not depend on Pr_b.

The average dependence of ΔK_2 on K^*_{Tg} was determined for each range of Re_b and these relations were referred to the average values of Re_b in that range. The dependence of ΔK_2 on Re_b for various K^*_{Tg} was obtained from these average curves and used to find smooth relations between K and K^*_{Tg} for various Re_b.

The resulting relations have the form

$$\Delta K_2 = (1.72 \cdot 10^6/\mathrm{Re}_b^{0.303}) K^*_{Tg} \tag{9}$$

for $\mathrm{Re}_b = 5 \cdot 10^3 - 2.10^4$; $K^*_{Tg} = 0 - 0.7 \cdot 10^{-5}$,

$$\Delta K_2 = (8.29 \cdot 10^9/\mathrm{Re}_b^{1.16}) K^*_{Tg} \tag{10}$$

for $\mathrm{Re}_b = 2 \cdot 10^4 - 10^5$; $K^*_{Tg} = 0 - 0.7 \cdot 10^{-5}$,

$$\Delta K_2 = (1 - 1{,}72 \cdot 10^6 \, K^*_{Tg}/\mathrm{Re}_b^{0.303})^{-1} - 1 \tag{11}$$

for $\mathrm{Re}_b = 5 \cdot 10^3 - 2 \cdot 10^4$; $K^*_{Tg} = -0{,}3 \cdot 10^{-5} - 0$,

$$\Delta K_2 = (1 - 8.29 \cdot 10^9/\mathrm{Re}_b^{1.16})^{-1} - 1 \tag{12}$$

for $\mathrm{Re}_b = 2 \cdot 10^4 - 5 \cdot 10^4$; $K^*_{Tg} = -0.3 \cdot 10^{-5} - 0$. Equations (9)–(12) are valid for $\mathrm{Pr}_b = 3$–10.

The relations obtained in the present paper enable one to perform practical calculations of unsteady heat transfer during the heating of a liquid in a channel for various laws of variation of the wall temperature or the heat flux density at the walls. As is clear from the above relations, the unsteady heat-transfer coefficient in the present case depends on two thermal unsteadiness criteria, K_q and K^*_{Tg}, one of which contains $\partial q_w/\partial \tau$ and the other, $\partial t_w/\partial \tau$. It should be noted that in calculating actual unsteady heat-transfer processes, in contrast with steady-state processes, it is impossible to specify either q_w or t_w beforehand. Both of these quantities are determined in the process of solving the adjoint heat-transfer problem for the flux density in the process of solving the adjoint heat-transfer problem for the flux density and the wall temperature. In view of the dependence of the heat-transfer coefficient on the unsteady boundary conditions, the present problem is ordinarily solved by the method of successive approximations. Therefore, it is not of fundamental importance whether $\partial q_w/\partial \tau$ or $\partial t_w/\partial \tau$ enters the thermal unsteadiness criteria, since $\partial q_w/\partial \tau$ and $\partial t_w/\partial \tau$ are related by Eq. (2).

The study showed that for the flow of a liquid in channels, just as for gases, the calculation of unsteady heat transfer using a quasisteady turbulence structure leads to errors that are inadmissible in practice.

NOTATION

a, thermal diffusivity of liquid; c_p, specific heat; d, inside diameter of pipe; g = 9.8 m/sec^2; G, mass flow rate; Fo = $a\tau/r_0^2$, Fourier number; K = $\mathrm{Nu}/\mathrm{Nu}_0$; K^*_{Tg}, $K_q = (\partial q_w/\partial \tau) \cdot (d^2/q_w a)$, dimensionless criteria describing time dependence of t_w and q_w; Nu, Nusselt number for unsteady conditions; Nu_0, Nusselt number for unsteady conditions determined from quasisteady relations; p, pressure; r_0, pipe radius; q_W, heat flux density; $q = q_W r_0/\lambda t_{b0}$; Re, Reynolds number; Pr, Prandtl number; t, temperature; t_{b0}, inlet temperature; u_{max}, axial velocity; w, mean flow rate; x, longitudinal coordinate; $X = 4xu_{max}/dPrRew$; α, heat-transfer coefficient; β, volumetric coefficient of expansion; λ, thermal conductivity; τ, time. Indices: w, wall temperature; b, mean bulk temperature of stream.

LITERATURE CITED

1. V. K. Koshkin, É. K. Kalinin, G. A. Dreitser, and S. A. Yarkho, Unsteady Heat Transfer [in Russian], Mashinostroenie, Moscow (1973).
2. B. S. Baibikov, G. A. Dreitser, É. K. Kalinin, and A. S. Neverov, Teplofiz. Vys. Temp., 10, No.6 (1972).
3. G. A. Dreitser, É. K. Kalinin, and V. A. Kuz'minov, Inzh.-Fiz. Zh., 25, No.2 (1973).
4. B. S. Baibikov, G. A. Dreitser, V. G. Izosimov, and É. K. Kalinin, in: Proceedings of the All-Union Correspondence Institute of Mechanical Engineering [in Russian], Vol.9, No.2, Gidravlika (1973).
5. I. S. Kochenov and Yu. M. Nikitin, Teplofiz. Vys. Temp., 8, No.2 (1970).
6. G. A. Dreitser, V. D. Evdokimov, and V. F. Chetyrin, in: Proceedings of the All-Union Correspondence Institute of Mechanical Engineering [in Russian], Vol.9, No.2, Gidravlika (1973).
7. S. S. Kutateladze and V. M. Borishanskii, Heat-Transfer Handbook [in Russian], GÉI (1959).
8. S. S. Filimonov and B. A. Khrustalev, in: Heat Transfer [in Russian], Izd. Akad. Nauk SSSR, Moscow (1962).
9. Yu. N. Kuznetsov and V. P. Belousov, Teplofiz. Vys. Temp., 8, No.6 (1970).
10. Yu. N. Kuznetsov and V. P. Belousov, Teplofiz. Vys. Temp., 10, No.1 (1972).

EXPERIMENTAL STUDY OF HYDRODYNAMIC AND HEAT-TRANSFER PROCESSES IN THE DOWNWARD MOTION OF A TWO-PHASE FLOW UNDER ANNULAR AND DISPERSED-ANNULAR CONDITIONS

B. G. Ganchev and A. B. Musvik

UDC 532.59:536.242

Relationships are derived for determining the average thickness of a liquid film and the predominant frequency of the wave motion on its surface under conditions of two-phase flow; relationships are also derived for calculating the hydraulic resistance and the rate of heat transfer to the film under these conditions.

A special characteristic of descending two-phase flows is the possibility of realizing an annular situation for any arbitrarily small rates of flow of the gas phase (in the limiting case, the free descent of the liquid). With increasing rate of gas flow, some of the liquid passes into the core of the flow, producing a dispersed-annular situation.

N. É. Bauman Moscow Higher Technical School.

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol.31, No.1, pp.13-20, July, 1976. Original article submitted February 18, 1975.