3. Yu. Stasyuslyavichyus and A. Skrinska, Heat Transfer in Transversely Streamlined Bundles of Finned Tubes [in Russian], Mintis, Vil'nyus (1974).
4. V. A. Lokshin and V. N. Fomina, "Generalization of data on experimental study of finned tubes," Teploenergetika, No. 6, 36-39 (1978).
5. A. Zhukauskas, V. Makaryavichyus, and A. Shlanchyauskas, Heat Transfer in Bundles of Tubes in Transverse Stream of Fluid [in Russian], Mintis, Vil'nyus (1968).
6. A. A. Zhukauskas, R. V. Ulinskas, and K. F. Martsinauskas, "Dependence of local heat transfer within stagnation zone of streamlining on geometry of tube bundle," Tr. Akad. Nauk Lit. SSR, Ser. B, 6(91), 115-126 (1975).
7. Y. N. Chen, "Fluctuating lift forces of Karman vortex streets on single circular cylinders and on tube bundles. Part 1: Vortex street geometry of single circular cylinder. Part 2: Lift forces on single cylinders. Part 3: Lift forces on tube bundles," Trans. ASME, Ser. B, J. Eng. Ind., 94, No. 2, 603-628 (1972).
8. Y. N. Chen, "Flow-induced vibration and noise in tube-bank heat exchangers due to von Karman streets," Trans. ASME, Ser. B, J. Eng. Ind., 90, No. 1, 134-146 (1968).
9. W. A. Mair, P. D. F. Jones, and R. K. W. Palmer, "Vortex shedding from finned tubes," J. Sound Vib., 39, No. 3, 293-296 (1975).
10. R. Hickling, Aerohydrodynamic Noise in Engineering [Russian translation], Mir, Moscow (1980).
11. Yu. A. Koshmarov, S. B. Svirshevskii, and E. N. Inozemtsev, "Heat transfer at and drag of finned tubes at low values of Reynolds number," in: Topical Collection of Sci. Tr. Mosk. Aviats. Inst., No. 463, Moscow (1978), pp. 33-37.
12. V. F. Yudin and L. S. Tokhtarova, "Dependence of heat transfer and drag on number of transverse rows of finned tubes in crisscross and corridor bundles," Energomashinostroenie, No. 4, 41-42 (1971).

EFFECT OF A CHANGE OF THE TURBULENT STRUCTURE OF A FLOW ON UNSTEADY HEAT EXCHANGE UPON HEATING OF GASES AND LIQUIDS IN PIPES

G. A. Dreitser

UDC 536.24

The article presents the results of experimental investigations of the unsteady heat exchange upon heating of gases and liquids and of the change in heat liberation from the pipe walls, as well as of the generalization of the experimental data which confirm the model of the effect of a change in the turbulent structure of the flow on the heat exchange.

Earlier investigations of the heat exchange accompanying the heating of a gas in a channel and of the change of heat flow density on the wall vs time [1] showed that the effect of the thermal nonsteady state on the heat emission coefficient increases with decreasing Reynolds number. The results of [1] were obtained chiefly for $Re_b = 8\cdot10^4-5.8\cdot10^5$, and the pipes used had almost equal diameters (d = 5.56 and 5.39 mm). It is therefore of interest to investigate unsteady heat exchange accompanying turbulent flow in a pipe with smaller Reynolds numbers Re_b and to verify the previously obtained theoretical dependences in pipes with other diameters.

An analysis in [2] showed that the difference between the unsteady and the quasisteady heat emission coefficients is due to the change of turbulent structure of the flow when the wall temperature increases or decreases. The main part in this is played by the nonsteady state of the turbulent boundary conditions $\partial T_w/\partial \tau$ which, as was shown in [3, 4], is most conveniently taken into account by the parameter

Sergo Ordzhonikidze Moscow Aviation Institute. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 43, No. 6, pp. 898-905, December, 1982. Original article submitted November 30, 1981.

 0022-0841/82/4306-1320$07.50

$$K_{Tg}^{*} = \frac{\partial T_w}{\partial \tau} \beta_w d \sqrt{\frac{\lambda}{c_p g G}}. \quad (1)$$

Investigations with water [5-7] showed that in distinction to gases, the deviation of the unsteady heat emission coefficient from the quasisteady-state value in the given case is due to the superposition of nonsteady thermal conductivity on steady convective heat exchange, as well as to the effect of the nonsteady-state boundary conditions on the turbulent structure of the flow. The relation between these effects depends on the channel diameter. Therefore, the generalizing dependences for unsteady heat exchange upon change of the thermal load and constant flow rate of the liquid were obtained in the form

$$K = 1 + \Delta K_1(K_q,\ \mathrm{Re}_b,\ \mathrm{Pr}_b) + \Delta K_2(K_{Tg}^{*},\ \mathrm{Re}_b), \quad (2)$$

where ΔK_1 is the change of K caused by nonsteady-state thermal conductivity; $K_q = \frac{\partial q_w}{\partial \tau} \frac{d^2}{q_w a}$, corresponding parameter of thermal nonsteadiness; and ΔK_2, change of K due to the change of the turbulent structure of the flow, and depending on the parameter K_{Tg}^{*} determined by (1). If we compare the values of $\Delta K_2 = K - 1 - \Delta K_1$ for liquids with the values of $\Delta K_2 = K - 1$ for gases, we can evaluate the correctness of the model of the effect of variable wall temperature on the structure of the turbulent flow and on unsteady heat exchange explained in [1, 3, 4].

Experiments with unsteady heat exchange upon heating of air were carried out in a pipe with inner diameter d = 12.44 mm, wall thickness δ = 0.165 mm, length L = 1209 mm. The pipe was heated by directly passing low-voltage ac through it. The following types of nonsteady change of the boundary conditions were investigated: increase of the wall temperature with stepped or stepless increase of heat liberation in the wall and lack of initial heat liberation, and decrease of wall temperature with stepped or stepless decrease of heat liberation in the pipe wall. The flow rate of air was set beforehand and remained unchanged during the experiment.

During the experiments we recorded changes of the temperature of the outer pipe wall vs time in seven sections which were situated at the following distances from the point where heating began; x/d = 4.97, 17.3, 29.6, 42, 54.5, 67.4, 79.2; we also recorded the temperature of the stream at the inlet to and the outlet from the experimental section, the air pressure at the inlet and outlet, the voltage drop, and the intensity of the current passing through the pipe.

For determining the unsteady heat emission coefficient

$$\alpha(x,\ \tau) = \frac{q_w(x,\ \tau)}{T_w(x,\ \tau) - T_b(x,\ \tau)} \quad (3)$$

it is indispensable to know the time-dependent change of the mean mass temperature of the stream T_b (x, τ), of the wall temperature T_w (x, τ), and of the density of the heat flow on the wall q_w (x, τ). The values of T_w (x, τ) and q_w (x, τ) were determined from the solution of the inverse problem of thermal conductivity from the experimentally measured temperature of the outer wall surface T_H (x, τ) and the volumetric heat liberation q_V (x, τ), and from the previously determined heat leaks from the outer pipe surface q_H (x, τ). The temperature T_b (x, τ) was found from the solution of the linear equation of energy for the stream. The calculation of the heat emission coefficients was carried out for eight sections of the pipe, which had the following distances from the point where heating begins: x/d = 2.48, 11.1, 23.5, 35.8, 48.9, 60.9, 73.3, 84.5.

With constant flow rate of the gas, the unsteady heat emission is

$$\mathrm{Nu}_b = f(\mathrm{Re}_b,\ \mathrm{Pr}_b,\ T_w/T_b,\ x/d,\ K_{Tg}^{*}), \quad (4)$$

and the quasisteady heat emission is

$$\mathrm{Nu}_{b0} = f_0(\mathrm{Re}_b,\ \mathrm{Pr}_b,\ T_w/T_b,\ x/d). \quad (5)$$

The numbers Re_b, Pr_b, and Nu_b were determined from the mean mass temperature of the flow in the given section. From the same temperature we determined c_p and λ in the parameter K_{Tg}^{*} (1). The investigations [1] showed that Nu_b and Nu_{b0} depend equally on x/d but the effect of Re_b and T_w/T_b on them is different. The Pr_b number for gases is constant. Therefore, taking (4) and (5) into account, the object of the experiment is to determine

$$K = \frac{Nu_b}{Nu_{b0}} = f_1(K^*_{Tg}, \ Re_b, \ T_w/T_b). \tag{6}$$

The quasisteady value of Nu_{b0} was calculated by the formula

$$Nu_{b0} = 0.018\, Re_b^{0.8}\, (T_w/T_b)^{-0.5} \varepsilon_L, \tag{7}$$

where the correction for the initial section ε_L was taken for the hydrodynamic stabilization of the flow ahead of the section of heat exchange

$$\varepsilon_L = 1 + 0.5\,(d/x). \tag{8}$$

Formula (7) with a scatter of ±7% describes the experimental data on local steady-state heat emission obtained in the given pipe, with $Re_b = 6 \cdot 10^3 - 4 \cdot 10^5$, $T_w/T_b = 1.1-2.7$, during the preliminary experiments with steady-state regime. The method and the experimental installation are described in detail in [8].

The experiments were carried out with $Re_b = 7 \cdot 10^3 - 1.5 \cdot 10^5$; $T_w/T_b = 1-1.9$; gas pressure at the inlet $p' = (2-10) \cdot 10^5$ N/m^2, rate of change of the wall temperature $\partial T_w/\partial \tau = (-200-300)$ °K/sec, $K^*_{Tg} = (-0.7-0.8) \cdot 10^{-4}$.

With stepped increase of heat emission in the wall pipe, T_w increased more quickly for larger x/d. The stabilization time of T_w is the longer, the larger the thermal load, the samller Re_b, and the larger x/d. The coefficient K drops from 2-3 at the beginning of the process to 1. When the load is removed, T_w decreases more quickly for large x/d. At the beginning of the process K = 0.6-0.8, and then it increases to 1.

Stepless increase of the thermal load was ensured by increasing the electric heating approximately linearly for 2-10 sec. Then the temperature T_w increased more quickly, the larger x/d was, and the coefficient K dropped from 1.5-2 at the initial instant to 1 at the end of the process. With stepless decrease of the thermal load, the electric heating decreased for 2-10 sec. At the same time the parameter K decreased at the beginning of the process from 1 to 0.6-0.8, and then it increased to 1. With τ = const the value of K is the smaller, the larger x/d.

First the experimental points which were obtained with stepped change of heat liberation were analyzed. Since the principal parameters of unsteady heat exchange of gases K^*_{Tg}, Re_b, and T_w/T_b changed interconnectedly in the experiments, the experimental data were processed with the object of revealing the effect of these parameters on unsteady heat exchange. All the experimental points were divided into several ranges of Re_b and T_w/T_b. For each of these ranges we determined the dependences of K (or of ΔK_2) on K^*_{Tg} for different x/d. With $K^*_{Tg} > 0$ $\Delta K_2 > 0$ $(K > 1)$, and with $K^*_{Tg} < 0$ $\Delta K_2 < 0$ $(K < 1)$. The dependences of K on K^*_{Tg} are the same for all x/d, i.e., in the processing of $K = f_1(K^*_{Tg}, Re_b, T_w/T_b)$, the parameter K does not depend on x/d. When $K^*_{Tg} < 0$, K depends the more strongly on K^*_{Tg}, the smaller Re_b. With increasing T_w/T_b, K decreases. With $K^*_{Tg} < 0$, the effect of K^*_{Tg} on K also decreases with increasing Re_b. An increase of the temperature factor entails an increase of K, i.e., it lowers the effect of thermal unsteadiness on K. The obtained data agree satisfactorily with previously obtained results [1, 4].

The reduced effect of thermal unsteadiness on K with increased Re_b is due to the decreased relative change of turbulence on account of unsteady thermal influence because the level of turbulence increases rapidly with increasing Re_b. With increasing turbulent thermal conductivity the relative contribution of heat transfer also decreases because of unsteady thermal conductivity. With increasing T_w/T_b the temperature gradient $(T_w - T_b)$ increases, and the relative influence of a change in wall temperature (the derivative $\partial T_w/\partial \tau$) on the turbulent structure of the flow and on the heat exchange decreases. With increasing Re_b the effect of the temperature factor on unsteady heat exchange decreases.

The results of experiments with stepped change of the thermal load are generalized by the dependences:

1) Increasing wall temperature $(\Delta K_2 > 0)$

$$\Delta K_2 = K - 1 = \left(2 - 0.83\,\frac{T_w}{T_b}\right)(10.4 - 19.2\,Re_b \cdot 10^{-5}) \times$$
$$\times (K^*_{Tg} \cdot 10^4)^{(1.84 - 0.66 Re_b \cdot 10^{-5})} \tag{9}$$

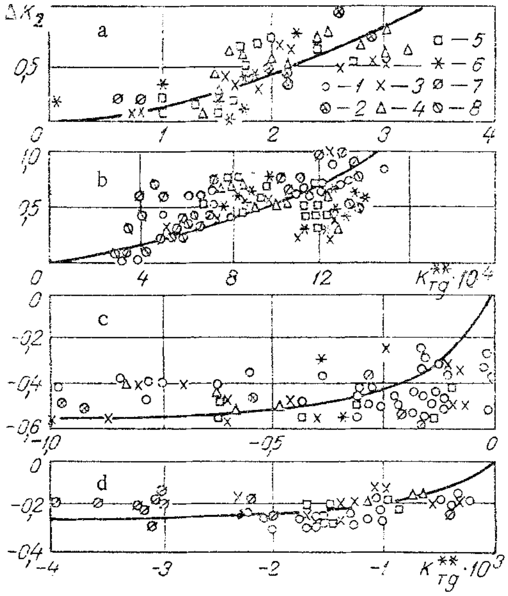

Fig. 1. Dependence of ΔK_2 on K^{**}_{Tg} for different Re_b with increasing (a, b) and decreasing (c, d) thermal load in heating gas, and T_w/T_b = 1.1-1.3: 1-8) x/d = 2.48, 11.1, 23.5, 35.8, 48.9, 60.9, 73.3, 84.5; a, c) $Re_b = (1\text{-}2)\cdot 10^4$; b, d) $Re_b = (1\text{-}1.5)\cdot 10^5$.

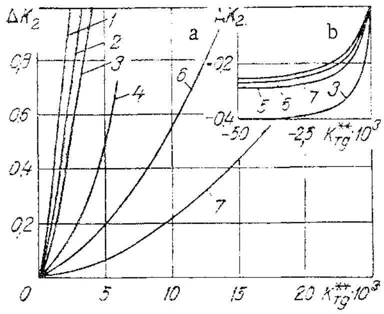

Fig. 2. Dependence of ΔK_2 on K^{**}_{Tg} for heating of gas with increasing (a) and decreasing (b) thermal load and T_w/T_b = 1.1-1.3; 1-7) $Re_b\cdot 10^{-4}$ = 0.085, 0.15, 0.25, 0.65, 0.75, 1.25, 2.

for $K^*_{Tg} = 0\text{-}0.4\cdot 10^{-4}$; $Re_b = 7\cdot 10^3\text{-}2.5\cdot 10^4$; T_w/T_b = 1-1.7;

$$\Delta K_2 = K - 1 = \left(2 - 0.83\,\frac{T_w}{T_b}\right)(4.6 - 1.46\,Re_b\cdot 10^{-5}) \times$$
$$\times (K^*_{Tg}\cdot 10^4)^{1.605 - 0.1 Re_b\cdot 10^{-5}} \quad (10)$$

for $K^*_{Tg} = 0\text{-}0.4\cdot 10^{-4}$; $Re_b = 2.5\cdot 10\ \text{-}2\cdot 10^5$; T_w/T_b = 1-1.7;

2) decreasing wall temperature ($\Delta K_2 < 0$)

$$\Delta K_2 = K - 1 = -1.25\,(2 - T_w/T_b)\,[1 -$$
$$- (0.325 + 0.206\,Re_b\cdot 10^{-5})\,|K^*_{Tg}|^{0.105 Re_b\cdot 10^{-5} - 0.27}] \quad (11)$$

for $K^*_{Tg} = -0.4\cdot 10^{-4}\text{-} -0.05\cdot 10^{-4}$; $Re_b = 7\cdot 10^3\ \text{-}2\cdot 10^5$; T_w/T_b = 1-7;

$$\Delta K_2 = K - 1 = 1.25\left(2 - \frac{T_w}{T_b}\right)(4.85 - 2.2\,Re_b\cdot 10^{-5})K^*_{Tg}\cdot 10^4 \quad (12)$$

for $K^*_{Tg} = -0.05\cdot 10^{-4}\text{-}0$; $Re_b = 7\cdot 10^3\text{-}2\cdot 10^5$; T_w/T_b = 1-1.7.

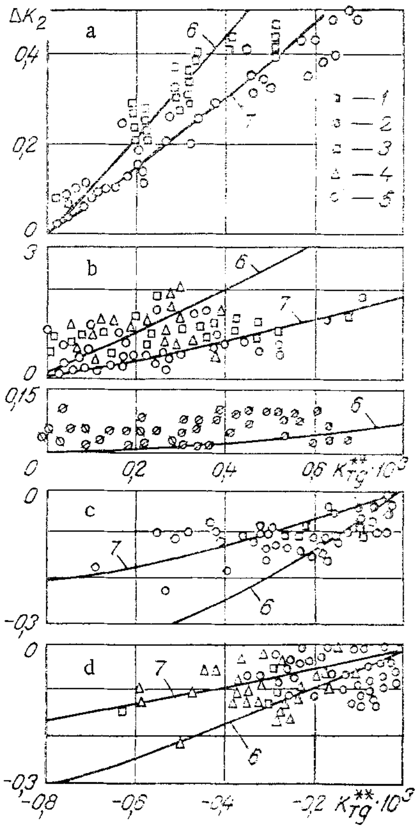

Fig. 3. Dependence of ΔK_2 on K_{Tg}^{**} for different Re_b and Pr_b in heating water and with increasing (a, b, c) and decreasing (d, e) thermal load: 1) Pr_b = 2-3; 2) 3-4; 3) 4-6; 4) 6-8; 5) 8-12; 6, 7) conversion by generalizing dependences via K_{Tg}^{*} for Pr_b = 3 and 12, respectively; a) $Re_b = (3\text{-}5)\cdot 10^3$; b) $(2\text{-}3)\cdot 10^4$; c) $(8.5\text{-}10)\cdot 10^4$; d) $(5\text{-}7.5)\cdot 10^3$; e) $(7.5\text{-}10\cdot 10^3$.

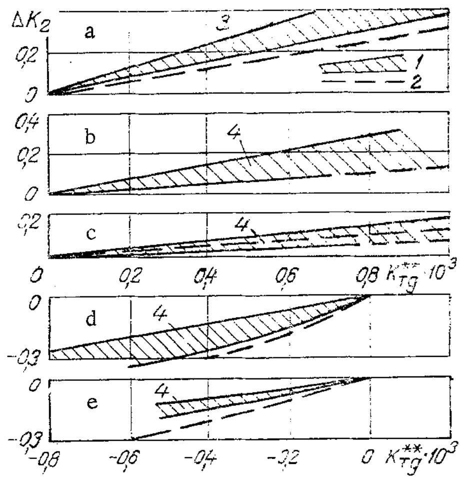

Fig. 4. Comparison of the data on unsteady heat exchange in heating gases and liquids: 1) water, Pr_b = 4-12 (3), Pr_b = 3-12 (4); 2) air; a, d) $Re_b = 8\cdot 10^3$; b, e) $Re_b = 2.5\cdot 10^4$; c) $Re_b = 5\cdot 10^4$.

Relations (9)-(13) were obtained for stepped increase of the thermal load from zero initial heat liberation ($q_{V1} = 0$), and stepped decrease of the thermal load with zero final heat liberation ($q_{V2} = 0$); to verify the possibility of using these relations, they were compared with the results of experiments with stepless change of heat liberation. The experimental data for stepless changes of heat liberation agree perfectly satisfactorily with the dependence (9)-(12) for their stepped change. Earlier [1, 4] it was shown that the data for different regularities of change of heat liberation in walls, obtained with pipes with smaller diameters, also agree well with each other.

Thus, dependences (9)-(12) may be applied while using the parameter K^*_{Tg}, determined by (1), for the heating of gases and for different relationships of change in heat flow density on the wall or in wall temperature vs time. The investigation showed that in a wide range of changes of the Re_b numbers, the unsteady heat emission coefficient does not depend on the regularity of change of the wall temperature or of the heat flow density on the wall, but that it is unambiguously determined by the derivative $\partial T_w/\partial\tau$ or by the corresponding dimensionless parameter K^*_{Tg}.

As previously mentioned, a comparison of the values $\Delta K_2 = K - 1$ for gases and $\Delta K_2 = K - 1 - \Delta K_1$ for liquids makes it possible to evaluate the correctness of the model of the effect of variable wall temperature on the turbulent structure of the flow and the intensity of heat exchange, adopted in [1, 3, 4]. According to this model, the change in turbulence of the flow near the wall and of the heat exchange is the greater, the larger the product $\frac{\partial T_w}{\partial\tau}\beta_w$ or the corresponding dimensionless parameter K^*_{Tg} (1).

The corresponding comparison showed that the values of ΔK_2 for gases and liquids upon their heating and with equal K^*_{Tg} and Re_b do not coincide (for gases we took points for $T_w/T_b \to 1$, i.e., for conditions close to isothermal ones, in order to eliminate the effect of variable density). The reason is that with constant Re_b, $\frac{\partial T_w}{\partial\tau}\beta_w$ and d, the parameter K^*_{Tg} depends on the Re_b number. In fact,

$$K^*_{Tg} = \frac{\partial T_w}{\partial\tau}\beta_w\sqrt{\frac{d}{g}}\sqrt{\frac{4}{\pi\,Re_b Pr_b}} = K^{**}_{Tg}\sqrt{\frac{4}{\pi\,Re_b Pr_b}}, \tag{13}$$

where

$$K^{**}_{Tg} = \frac{\partial T_w}{\partial\tau}\beta_w\sqrt{\frac{d}{g}} \tag{14}$$

is the parameter of thermal unsteadiness, which does not depend on Re_b and Pr_b. Since Pr_b is larger for liquids than for gases, the parameter K^*_{Tg} for gases is larger with equal $\frac{\partial T_w}{\partial\tau}\beta_w\sqrt{\frac{d}{g}}$, and therefore its effect on unsteady heat exchange is smaller.

Proceeding from these considerations, we processed the available experimental points of unsteady heat exchange of air, given in [1, 4] and in the present article, and of water [5-7], with the object of obtaining the dependences of ΔK_2 on K^{**}_{Tg}, Re_b, T_w/T_b for gases and of ΔK_2 on K^*_{Tg}, Re_b, Pr_b for liquids. Figure 1 presents the dependences of ΔK_2 on K^{**}_{Tg} for different ranges of Re_b for gases, and Fig. 2 shows the averaging dependences of ΔK_2 on K^{**}_{Tg} with different Re_b and with T_w/T_b = 1.1-13. The dependence of ΔK_2 on K^{**}_{Tg} is the stronger, the smaller Re_b and T_w/T_b. The formulas for these dependences are obtained by replacing the parameter K^*_{Tg} by K^{**}_{Tg} in (9)-(12) in accordance with the relation (13).

The results of conversions for unsteady heat exchange in heating liquids are presented in Fig. 3 for increasing ($\Delta K_2 > 0$) and for decreasing ($\Delta K_2 < 0$) thermal load. This illustration shows the results of calculations of separate points belonging to different ranges of Pr_b numbers and the results of conversion of the average empirical dependences for different Pr_b, given in [5], by replacing K^*_{Tg} in them, in accordance with (13), by K^{**}_{Tg}.

A comparison of the results obtained for gases and liquids is shown in Fig. 4. The hatched regions for liquids belong to the range of changes of Pr_b = 3-10 which take place in experiments with water; the dashed lines concern the data obtained with air. It can be seen from this figure that with equal K^{**}_{Tg} and Re_b, the values of ΔK_2 for liquid and gas (with T_w/T_b close to 1) practically coincide, whereas their thermal coefficients of volume expansion β_w differ by a factor of 40. This confirms the correctness of the model of the effect of a change in the turbulent structure of a flow on the unsteady heat exchange, presented in [1, 3, 4].

Thus, the experiments and their analysis showed that a change in the turbulent structure of flow has a substantial effect on unsteady heat exchange both in gases and liquids. Therefore, the theoretical models of unsteady heat exchange based on the hypothesis of quasisteady structure of turbulent flow cannot yield satisfactory results.

NOTATION

a is the thermal diffusivity; c_p, heat capacity; d, inner pipe diameter; G, mass flow rate; $g = 9.8$ m/sec^2; q_w, heat flow density on the wall; T_w, wall temperature; T_b, mean-mass flow temperature; x, distance from inlet; α, heat emission coefficient; β_w, thermal coefficient of volume expansion of gas or liquid at the wall temperature; λ, thermal conductivity; δ, thickness of the pipe wall; τ, time; $K = Nu/Nu_o$; Nu, unsteady-state Nusselt number; Nu_o, quasisteady-state Nusselt number; Re, Reynolds number; Pr, Prandtl number; and K_q, K_{Tg}^{*}, K_{Tg}^{**}, parameters of thermal unsteadiness. Subscripts: w, relating to wall temperature; b, relating to mean-mass flow temperature.

LITERATURE CITED

1. V. K. Koshkin, É. K. Kalinin, G. A. Dreitser, and S. A. Yarkho, Unsteady Heat Exchange [in Russian], Mashinostroenie, Moscow (1973).
2. B. S. Baibikov, G. A. Dreitser, É. K. Kalinin, and A. S. Neverov, "The effect of the Reynolds number on unsteady convective heat exchange in a pipe under changing thermal load," Teplofiz. Vys. Temp., 10, No. 6, 1046-1055 (1972).
3. G. A. Dreitser, É. K. Kalinin, and V. A. Kuz'minov, "Nonsteady heat exchange with different regularities of cooling of hot gas in pipes," Inzh. Fiz. Zh., 25, No. 2, 208-216 (1973).
4. B. S. Baibikov, G. A. Dreitser, V. G. Izosimov, and É. K. Kalinin, "Analysis of the results of the experimental investigation of unsteady convective heat exchange under changing thermal load," Tr. VZMI, Gidravlika, 9, No. 2, 110-117 (1973).
5. G. A. Dreitser, V. D. Evdokimov, and É. K. Kalinin, "Experimental investigation of the effect of a change of heat flow and flow rate on the unsteady convective heat exchange with turbulent flow of a liquid in a pipe," Tr. VZMI, Gidravlika, 10, No. 3, 127-147 (1974).
6. G. A. Dreitser, V. D. Evdokimov, and É. K. Kalinin, "Unsteady convective heat exchange upon heating of a liquid in a pipe by a variable heat flow," Inzh. Fiz. Zh., 25, No. 1, 5-12 (1976).
7. G. A. Dreitser and V. D. Evdokimov, "Generalization of the experimental data on unsteady heat exchange upon flow of a liquid in pipes with different diameters," Tr. VZMI, Gidravlika, 29, No. 4, 81-96 (1975).
8. G. A. Dreitser, P. M. Markovskii, and V. F. Chetyrin, "Unsteady convective heat exchange in a pipe with turbulent flow in the region of small Reynolds numbers," Tr. VZMI, Gidravlika, 9, No. 2, 190-209 (1973).