CORRESPONDENCE BETWEEN HEAT-TRANSFER COEFFICIENTS IN STEADY AND UNSTEADY PROCESSES

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An experimental study is made of the unsteady flow of heat through an element of a heat-exchanger wall for various flow conditions of the heat-carrying medium. These processes are compared with the processes occurring in the simple heating of the element (i.e., with one end thermally insulated to prevent through-flow of heat). The comparison is made for the same flow conditions of the heat-carrying medium. The conclusions of the thought experiment described in [1] are confirmed.

Studies on the heating of solid bodies under identical conditions have shown that for a given temperature difference the coefficient of heat transfer is different for different bodies [1]. Accordingly, one is led to consider the question of the relationship between the tempos of heat transfer in steady and unsteady processes.

The thought experiment described in [1] (see also N. V. Shumakov, Doctoral Dissertation of G. M. Krzhizhanovskii Institute of Power Engineering, Moscow, 1955) implies that there is a considerable lack of correspondence between these processes.

Experiments on the flow of heat through a body simulating an element of a heat-exchanger wall under start-up, changeover, and steady-state conditions and on heat flow in the body under conditions of simple heating (i.e., with an end of the body thermally insulated so that there is no through-flow of heat) confirm that the heat-transfer coefficient behaves differently in these processes.

The experiments were performed on a two-channel apparatus (apparatus D), which has much in common with apparatus B previously described. The liquid-carrying channels between which heat exchange occurs are of rectangular cross section (30.2×39.9 and 30.8×39.8 mm^2) and length 1.8 m and are disposed in the vertical plane, the hot channel above the cold, to eliminate natural convection. The considerable thickness of the walls of the channels (21 mm) and the low thermal conductivity of the wall material (Textolite, $\lambda = 0.2$ kW/m·deg) enable an isothermal flow to be obtained in the channels. Hot water flows in one of the channels and cold in the other. At a distance ~28 bore sizes from the tube inlet there is located in the wall separating the channels a moveable "slider" carrying the measuring body (cobalt or silver cylinders of diameter 15 mm and length $\bar{R} = 50$ mm, designated Co-50 and Ag-50 below). Insulation

TABLE 1. Experimental Conditions

Experiment No.	Co-50 calorimeter		Experiment No.	Ag-50 calorimeter	
	Re_H	Re_C		Re_H	Re_C
1	1800	—	8	1800	—
2	4500	—	9	4500	—
3	7200	—	10	1800	3300
4	1800→7200	—	11	7200	3300
5	1800	3400			
6	7200	3400			
7	1800→7200	3400			

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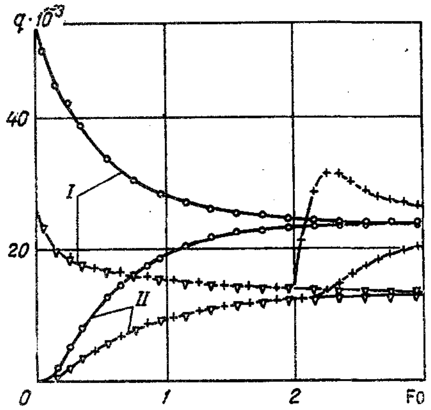

Fig. 1

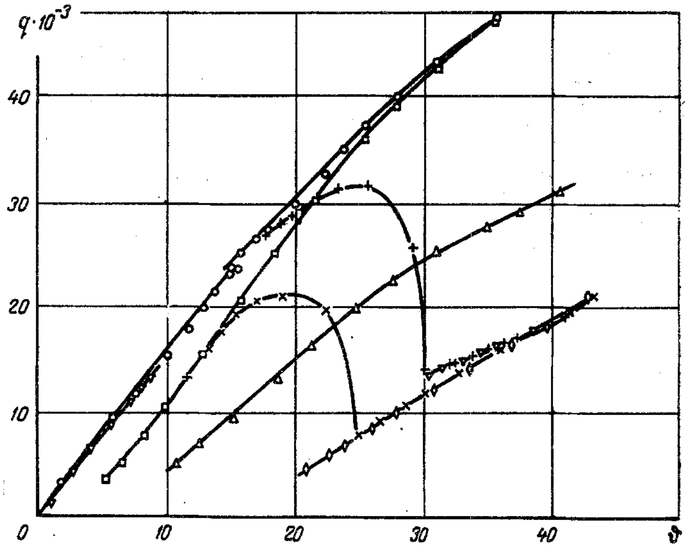

Fig. 2

Fig. 1. Time dependence of heat flux, $q = f(Fo)$; $q_{con} = q \cdot 1.163\ W/m^2$ (for notation see Fig. 4). I refers to q_1 and II to q_2.

Fig. 2. Heat flux as function of temperature difference, $q = q(\vartheta)$; $q_{con} = q \cdot 1.163\ W/m^2$ (for notation see Fig. 4).

was by means of granulated cork and also a vacuum (not worse than 10^{-4}-$5 \cdot 10^{-5}$ mm Hg). The quality of the insulation, both cork and vacuum, was of the same order, although the use of a vacuum substantially complicates the experiment. The junctions of eight thermocouples were located in the measuring body (at distances $y = x/R = 0;\ 0.1;\ 0.2;\ 1-\sqrt{3}/3;\ \sqrt{3}/3;\ 0.8;\ 0.9;\ 1.0$).

Each of the channels of the apparatus together with the supply tubes and a respective U-10 thermostat forms a closed circuit. Thermocouples monitor the water temperature at the inlet and outlet of each channel.

In one of the extreme positions of the slider the calorimeter is positioned in the wall separating the channels; in the other, the measuring cylinder is moved into a special chamber for initial thermostatting to the prescribed temperature.

In the experiments on simple heating, because of the increase in the dimensions of the calorimeter resulting from the need to insulate the end at $y = 0$, part of the side wall of the lower channel was removed and the channel was connected to the chamber for initial thermostatting. The experimental procedure was much the same as described previously [1]. The experimental data were analyzed through the solutions of the inverse problem in successive intervals [2]. The magnitude of the interval into which the process was split up in time was $\Delta Fo = 0.1$ for the Co-50 calorimeter and $\Delta Fo = 0.5$ for the Ag-50 calorimeter. The experiments performed are listed in the table.

In all the experiments the water temperature at the inlet to the hot channel was maintained at $t_H = 75°C$; in the cold channel $t_C = 25°C$. The initial temperature of the measuring body $t_0 = 25°C$. In the table the dashes in the Re_C column mean that the corresponding experiments (Nos. 1-4, 8, 9) relate to simple heating of the body (surface at $y = 0$ thermally insulated). The two numbers in the Re_H column interconnected by an arrow (experiments Nos. 4 and 7) show that the corresponding experiment relates to the heating of the body under changeover conditions, i.e., when the flow of the heat-carrying medium is changed from $Re_H' = 1800$ to $Re_H'' = 7200$. The conditions investigated in the remaining experiments can be identified with the start-up mode of a heat exchanger.

Thus, three different types of unsteady heat flow in a solid body were investigated: the start-up and changeover modes of a heat exchanger, and simple heating of the body for fixed and step-wise variable conditions at the inlet.

Figure 1 shows the time dependence of the heat flux density $q_1(\tau)$ and $q_2(\tau)$ at the boundaries $x = R$ and $x = 0$ for three experiments (Nos. 5-7). Two of them (Nos. 5 and 6) simulate start-up modes and the

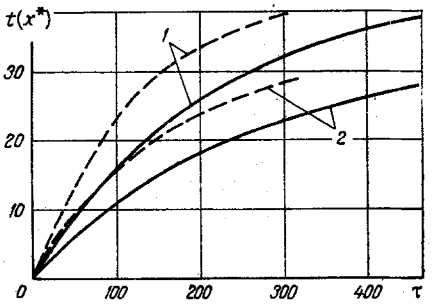

Fig. 3. Temperature at $x = x^*$ in experiments on simple heating. Solid curves correspond to Co-50 calorimeter and dashed to Ag-50. Reynolds number Re: 1) 4500, 2) 1800. Time τ in seconds.

third (No. 7) the changeover mode of a heat exchanger. In the start-up experiments the functions $q(\tau)$ are smooth and monotonically approach their steady-state values ($q_1(\tau)$ decreasing and $q_2(\tau)$ increasing). In the changeover mode (experiment No. 7) the sharp increase in the flow velocity of the heat-carrying medium disturbs the monotonic decrease of $q_1(\tau)$: the heat flux increases sharply, but after a time Fo $\approx$ 0.25-0.30 the function $q(\tau)$ again becomes monotonically decreasing, tending "from above" towards the $q_1(\tau)$ corresponding to the new flow conditions.

Figure 2 shows the heat flux q as a function of the instantaneous temperature difference $q(\vartheta)$ for experiments Nos. 1-7. The behavior of the heat flux at the hot end is shown by the curves $q_1(\vartheta_H)$ going from the top right in the direction of decreasing temperature difference. The functions $q_2(\vartheta)$, on the other hand, starting from $\vartheta_C = 0$ increase with increasing ϑ_C. In the changeover mode the function $q_1(\vartheta_H)$ varies smoothly when the flow velocity of the heat-carrying medium is increased and approaches the form characteristic for the new flow conditions. Due to the inertia of the solid body, the entire system goes over into the new mode after a time of order Fo $\simeq$ 0.5 ($\tau \simeq$ 70 sec). The same conclusion can be reached from an analysis of the results of the experiments on simple heating of the body with changeover of the inlet conditions (experiment No. 4). Here the function $q(\vartheta)$ varies smoothly from the value characteristic for experiment No. 1 to the value characteristic for experiment No. 3 (Fig. 2). All this is better illustrated by the behavior of the heat-transfer coefficients (see below).

Experiments Nos. 1 and 8 and Nos. 2 and 9 can be regarded as pairs of experiments under identical external conditions. A comparison of the temperature-versus-time curves for the coordinate x* corresponding to the mean temperature (Fig. 3) confirms one of the consequences of the basic coupling equation [3]: the heat-transfer coefficient α in these experiments is a variable quantity, decreasing as the process evolves. Let us compare its behavior under these conditions of simple heating with its behavior in heat-transfer processes.

Figure 4 shows plots of the heat-transfer coefficient versus temperature difference, $\alpha(\vartheta)$, at the heated and cooled surfaces of the measuring body of the calorimeter. If unsteady transfer of heat takes place at constant inlet flow conditions of the heat-carrying medium (start-up mode), then at small Re_H the magnitude of the heat-transfer coefficient remains constant in the process.

At the more intense flow in experiments Nos. 6 and 11 (Re_H = 7200, and also in experiments at Re_H = 4500 now shown here), when the temperature difference in the process changes greatly, the quantity α_H increases in proportion to $(Pr_f/Pr_{st})^{0.25}$ [4].

A comparison of the values of α_H for the same temperature difference in experiments Nos. 5 and 10 and Nos. 6 and 11 shows that α_H for the Co-50 calorimeter is somewhat greater than for the Ag-50 calorimeter. This difference is not so pronounced as in processes of simple heating [1] and amounts to around 5-15%.

The value of α_H at the end of recording (Fo = 3 or τ = 420 sec for the Co-50 calorimeter, Fo = 20 or τ = 300 sec for the Ag-50 calorimeter) is close to the value of the heat-transfer coefficient under steady-state conditions in the given experiment, α_{st}. The latter quantity was determined in the following manner. After the heating process had been recorded, the calorimeter was left in its "working position" for not less than 25-30 min. The temperature distribution was assumed to be stationary after this time (formally taken as $\tau \to \infty$), and the heat flux was calculated in terms of the temperature drop $q_{st} = \Delta t\lambda/R$. Recording the temperature of the surface at $\tau \to \infty$ enables α_{st} to be calculated. The values of α_{st} are almost the same as the values of α_{nonst} corresponding to the end of recording of the process.

The value of the heat-transfer coefficient at the hot end exceeds the value given by Mikheev's formula by a factor of around 5 for Re_H = 1800, 1.5-2 for Re_H = 4500, and 1.3 to 1.5 for Re_H = 7200. This may perhaps be due to the small value of l/d in our experiments. Evidently, this question can only be resolved by studying unsteady heat transfer through an extended wall.

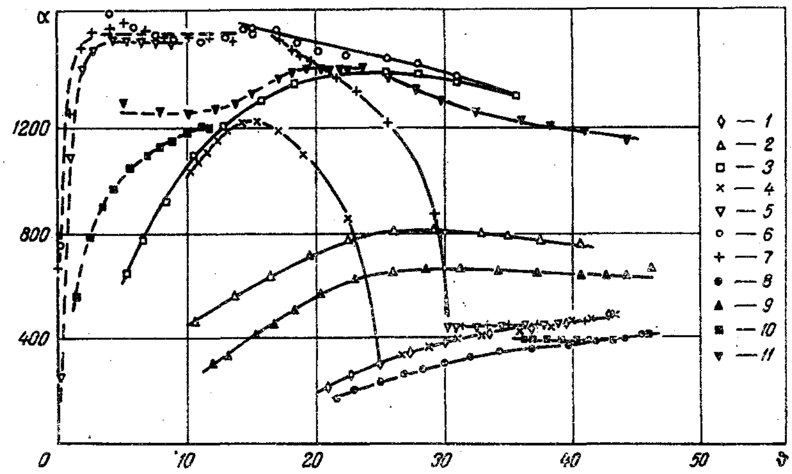

Fig. 4. Plots of heat-transfer coefficient versus temperature difference. Solid curves relate to heated end, dashed curves to cooled end. Numbers 1 to 11 correspond to experiments Nos. 1 to 11 respectively.

In the experiments on the simple heating of the solid bodies, α_H at the beginning of the process coincides with the value obtaining under heat-transfer conditions; it subsequently falls during the recorded stage by a factor of more than 2.

Thus, the heat-transfer coefficient behaves differently depending on whether the measuring body is simply heated or on whether heat is being transported through this same body heated under the same conditions of flow of hot liquid around it (see also Fig. 46 in [1]).

It is of interest to compare the time variation of the temperature field in a body under conditions of simple heating (Fig. 5a) and under conditions of unsteady heat transfer (Fig. 5b).

The space-time net method [5] was used to construct the temperature fields reproduced in these figures. The separate time (at top right) shows the temperature distribution in the measuring body of the calorimeter as $\tau \to \infty$.

The temperature of the surface being heated varies identically in the initial stage of the process in both cases; the rate of increase of surface temperature for simple heating begins to exceed that for heat-transfer conditions only from Fo $\simeq$ 0.5. The temperature drop over the thickness of the body $\Delta t = t(R) - t(0)$ is also identical in both cases up to Fo = 0.2; in the heat-transfer case Δt continues to increase for times Fo $\geq$ 0.2 due to the less rapid variation of the temperature of the cooled surface ($x = 0$) as it approaches its steady-state value ($\Delta t_{st} = 19.65°$ for Fo $\simeq$ 20). In the simple-heating case the temperature drop increases to $\Delta t = 16.9°$ at Fo = 0.3 and thereafter smoothly decreases; at Fo = 3.0 (end of continuous recording) it amounts to 4.31°C and at Fo $\simeq$ 15 the temperature drop $\Delta t = 1.25$°C. The temperature fields vary in a similar manner for bodies of different materials; the time required to reach what may be called the quasistationary state varies. For Co-50 this time equals Fo $\simeq$ 1.0, and for Ag-50 it is Fo $\simeq$ 3-4. This sort of variation of the temperature fields corresponds to the principle of superposition.

The behavior of the heat-transfer coefficient at the hot end is in complete accord with the above picture; the values of the heat-transfer coefficient under simple-heating and heat-transfer conditions are the same so long as the temperature fields in the body are the same. The decrease in the temperature drop in the body under simple-heating conditions (compared with the drop under heat-transfer conditions) leads to a decrease in the value of the heat-transfer coefficient (see Fig. 4).

As already noted, α varies by a factor of more than 2 in the experiments on simple heating. If the time for which the temperature is recorded were increased, one could expect an even larger variation.

In the changeover mode (experiment No. 7) α_H varies from a value corresponding to the initial Re_H = 1800 to a value close to that corresponding to the final Re_H = 7200. This is also observed in the simple heating of the body when the flow conditions of the heat-carrying medium are changed (experiment No. 4).

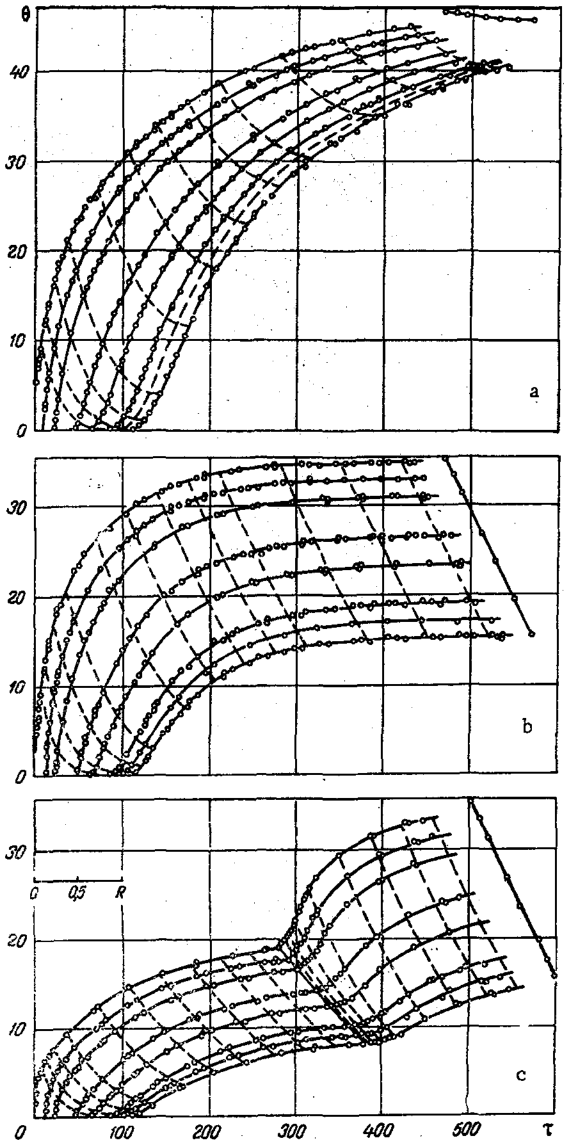

Fig. 5. Temperature field in Co-50 measuring body. a) In experiment No. 3 ($Re_H = 7200$; $\Theta(x, \tau) = t(x, \tau) - t_0 = f(x, \tau)$; solid curves show $\Theta(\tau)$, dashed curves show $\Theta(x)$. b) In experiment No. 6. c) In experiment No. 7.

We note that the shutter used to vary the flow conditions can be actuated in less than one second. The time required for the flow to stabilize hydrodynamically is of the same order. The time during which the most significant variation of α_H occurs is around 50-70 sec. Evidently, the variation of α_H in these experiments can only be ascribed to the readjustment of the temperature field in the solid body.

Let us consider how the temperature field varies in the changeover mode. The temperature field in experiment No. 7 is shown in Fig. 5c. Up to a time $\tau = 280$ sec it is identical to the field in experiment No. 5 ($Re_H = 1800$, $Re_C = 3400$). The variation of the field after $\tau = 280$ sec is due entirely to the change in the flow conditions at the hot end ($Re_H = 1800 \rightarrow 7200$). The temperature drop over the thickness of the body tends to the value corresponding to the conditions of experiment No. 6 ($Re_H = 7200$, $Re_C = 3400$).

The temperature of the surface at $x = R$ and so also the temperature drop likewise tend towards $t(R, \tau)$ and $\vartheta(R, \tau)$ from experiment No. 6. In the changeover mode $q(\tau)$ and $\vartheta(R, \tau)$ tend at different rates towards the forms characteristic for experiment No. 6, so that the heat-transfer coefficient increases smoothly to the value corresponding to the new flow conditions.

Thus, the boundary conditions established on one surface of the heat exchanger wall depend not only on the parameters characterizing the flow of the heat-carrying medium, but also on the conditions under which heat is removed from this surface. These conditions depend, in turn, on the rate at which heat is transported to the opposite surface and on the parameters of the wall itself. It follows from this that for given flow conditions and a given temperature difference the heat-transfer coefficient can take on a set of values, the value of α under steady conditions being the maximum for a given flow-wall system. These results confirm the conclusions of the thought experiment first devised in 1955.

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