HEAT EXCHANGE OF BUNDLES OF RODS PLACED AT AN ANGLE TO AN INCOMING STREAM OF LIQUID METAL

V. M. Borishanskii, M. A. Gotovskii,
V. B. Zhinkina, É. V. Firsova,
and L. L. Shneiderman

UDC 536.242

Results are presented of an experimental investigation of the heat exchange between liquid metals (Pr = 0.007 and 0.03) and bundles of tubes inclined at angles ψ = 30, 60, and 90° to the heat-transfer agent. The experiments were performed in the Pe number range (for the incoming flow) 10-600. Hints for the calculation of the heat-exchange coefficients are given.

Elements of convective heating surfaces over which a stream of heat-transfer agent flows at different angles constitute an appreciable fraction of the surface of multiflow and coiled heat exchangers and steam generators. It is therefore urgent to develop instructions that make it possible to determine the heating surface correctly without unjustified margins.

The heat exchange between bundles of tubes and liquid metals flowing in the longitudinal and transverse directions have been discussed quite extensively in [1-3]. Papers devoted to a theoretical [4] and experimental [5] investigation of heat exchange for an "oblique" incoming flow were published in 1965-1967.

In the present paper we report briefly results of an investigation of heat exchange in bundles of tubes arranged in checkerboard fashion and placed in angles of ψ = 90, 60, and 30° to the incoming flow of liquid metals with Pr numbers 0.007 and 0.03.

The constructions of the working sections and the circulation contours are similar to those given earlier in [6].

The working sections were packets of tubes of diameter 22 m and thickness 2.5 mm, arranged in checkerboard fashion. The bundle consisted of 9 rows of tubes in depth and 4 tubes along the front. The tubes of the bundle were placed in a rectangular duct at angles to the flow, as shown in Fig. 1.

The geometrical parameters of the bundles are given in Table 1.

The entry into the "oblique" bundle of tubes was organized in analogy with the tubes in transverse flow (ψ = 90°), by installing a rectangular diffusor and two equalizing gratings. Such an arrangement ensured uniform distribution of the flow ahead of the first row of the bundle.

Figure 1 shows a section of the investigated bundles in a plane perpendicular to the generators of the tubes. The shaded tubes were heated with alternating current, and the black tubes were calorimeters placed in the first and seventh depth rows, and were heated with direct current. The numbers on Fig. 1 show the unheated tubes, inside which were placed thermocouples to measure the temperature of the heat-transfer agent.

The mixing temperature of the heat-transfer agent was measured also at the entrance and exit from the bundle, using thermocouples in cartridges immersed in the flowing heat carrier.

The heating was with the aid of tubular heaters of steel Kh18N10T $\varnothing$ 14 × 1 mm, to which copper current leads of dimensions 14 × 4 mm were welded. The annular gap between the heater and the tube of the

I. I. Polzunov Boiler and Turbine Institute, Leningrad. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 19, No. 6, pp. 977-982, December, 1970. Original article submitted October 30, 1969.

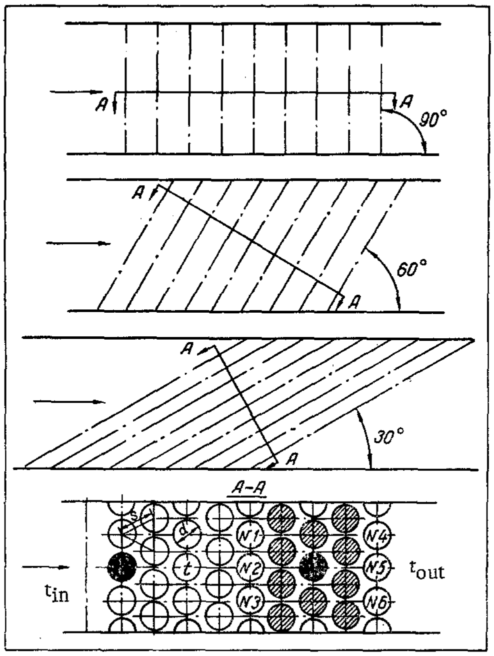

Fig. 1. Arrangement of the tubes in the bundles.

TABLE 1. Geometric Parameters of the Investigated Bundles

Geometric parameters	Bundle No. 1 $\psi = 30°$	Bundle No. 2 $\psi = 60°$	Bundle No. 3 $\psi = 90°$
Number of tubes in bundle, including the unheated inserts on the walls	36	36	27
Outside diameter of of tubes, mm	22	22	28
	height 200 width 106	height 200 width 106	250 105
Geometrical arrangement of rods	equilateral triangle		
Relative pitch of bundle S/d	1,2	1,2	1,25
Length of tubes between boards, mm	400	206	250

bundle was filled with powdered boron nitride, which has high thermal conductivity ($\lambda \sim 10$ kcal/m$^2 \cdot$ h $\cdot$ deg) and good electric insulating properties. In the experiments with the heat-transfer agent at Pr = 0.007, we used copper calorimeter tubes, and in the experiments with Pr = 0.03 we used tubes of Kh18N10T steel. In the tube walls of the copper calorimeters, there were through channels of 1.5 mm diameter, into which thermocouples capable of moving over the entire length were placed.

In the Kh18N10T steel calorimeters, the thermocouples in the capillaries were sealed into the wall by metallization. The junctions of the thermocouples were placed along the perimeter of the calorimeter cross section in a plane parallel to the direction of the flow and passing through the center of the tube. In a number of experiments with the copper calorimeter, the thermocouples were moved along the generatrices.

After a steady state was reached in the experiments, we measured the following quantities: the calorimeter wall temperatures in the first and seventh rows along the depth of the bundle; the temperature of the heat carrier at the entrance and exit from the working section, and also the temperatures of the heat-transfer agent flowing over the central section of the rods numbered 1-6 in Fig. 1; the electric power released at the calorimeters of the first and seventh rows and on the lateral heated tubes; and the quantity of heat-transfer-agent flow.

The electromotive force of the thermocouples determining the temperature of the heat-transfer agent was measured with type-R-330 potentiometers.

The electromotive force of the thermocouples installed in the calorimeter walls was either measured with the same potentiometers or recorded on the charts of automatic plotting potentiometers ÉPP-09 with a scale of 2 mV (attachment for the R-330).

All the thermocouples were calibrated directly in the loop before and after plotting the operating conditions. The standard was a thermocouple measuring the temperature of the liquid entering into the bundle.

The flow of the heat-transfer agent with Pr = 0.007 was measured with electromagnetic flow meters the specifications of which guaranteed an error not larger than ±2.5% of the maximum flow at the working temperature. The flow of the heat-transfer agent with Pr = 0.03 was determined with the aid of a nozzle with a heated piezometer.

The measurements made it possible to calculate the values of the average and local heat-exchange coefficients $\alpha = q/\Delta t$ for the tubes of the first and seventh rows. Here q is the average specific heat flux through the surface of the colorimeter tube, calculated from the formula

$$q = \frac{0.86\,IU}{\pi\, dl_{\text{vol}}} \ \text{kcal/m}^2\text{h}; \tag{1}$$

Δt is the average temperature differential, determined as the difference between the wall temperature averaged over the perimeter and the heat-transfer-agent.

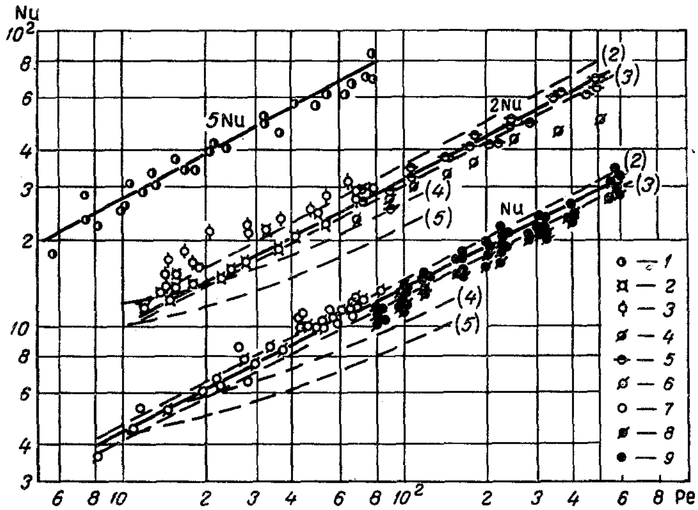

Fig. 2. Heat exchange of bundles of tubes in a stream of liquid metal: at $\psi = 90°$: 1) 7th row, Pr = 0.007; at $\psi = 60°$: 2) first row; 3) 7th row, Pr = 0.007; 4) 1st row; 5) 7th row. Pr = 0.03: at $\psi = 30°$: 6) 1st row; 7) 7th row. Pr = 0.007: 8) 1st row; 9) 7th row. Pr = 0.03. The numbers in the parentheses next to the curves refer to the formula numbers.

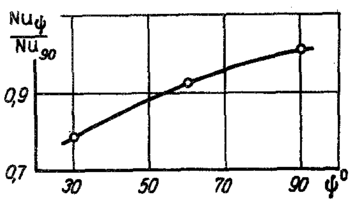

Fig. 3. Relative heat exchange in an "oblique" incoming flow (Nu_ψ) and in transverse flow over the tubes (Nu_{90}).

The wall temperature measured with the thermocouples was corrected to account for the depth of location of the hot junction.

The average wall temperature was determined by graphic integration.

The definitive heat-transfer-agent temperature in the expression for the temperature differential was assumed to be the temperature of the liquid at the cross section of the calorimeter.

In the present paper, the heat exchange was referred to the velocity $w = V/\Omega$ of the incoming flow.

The results of the experiments on heat exchange as functions of the velocity are shown in dimensionless coordinates (Nu = f(Pe)) in Fig. 2.

Heat exchange with liquid metal (Pr = 0.007) is practically independent of the number of the row in which a calorimeter is installed. With increasing Prandtl number (Pr = 0.03), a slight stratification appears in the heat exchange of the first and seventh rows, with the exchange of the deeper row somewhat higher than that of the first. This is due to the fact that when Pr is increased the hydrodynamics exert a larger influence on the heat exchange. The experiment on the heat exchange with the bundles (ψ = 30 and 60°) covered the range $10 < Pe < 600$.

The velocity of the heat-transfer agent varied in the range $0.03 < w < 0.25$ m/sec. The per-unit heat loads amounted to $q = (135\text{–}225) \cdot 10^3$ kcal/m^2 · h. Experiments with the bundle at $\psi = 90°$ were performed only with the heat-transfer agent with Pr = 0.007.

A certain decrease of the heat-exchange data at Pr = 0.03 in comparison with the data obtained with Pr = 0.007 is due, in our opinion, to the influence exerted on the heat exchange by a certain difference in the boundary condition on the surface of the calorimeter, owing to the different character of the transfer flow on the copper and steel surfaces.

Using the obtained data on heat exchange for bundles with the indicated geometry at ψ = 30, 60, and 90°, we plotted in Fig. 3 the dependence of the relative heat exchange on the angle of inclination of the surface to the flow direction

$$\frac{Nu_\psi}{Nu_{90}} = f(\psi) = \sin^{0.4}\psi,$$

where Nu_{90} is the heat exchange for transverse flow over the bundle of given geometry [7]. It follows from this plot that when the inclination of the surface is varied from $\psi = 90$ to 30°, the heat exchange is decreased 20%.

In Fig. 2, the experimental results for bundles at $\psi = 30$ and 60° are compared with the theoretical calculations of [4] and the empirical formulas of [5] for the corresponding spacings. The comparison shows a rather satisfactory agreement between the experimental results and the theoretical calculated lines corresponding to equations [4]:

$$Nu_\psi = 0.958\left(\frac{\Phi_1}{d}\right)^{0.5} Pe^{0.5}\left[\frac{\sin\psi + \sin^2\psi}{1+\sin^2\psi}\right]^{0.5} \tag{2}$$

for $t_{ts} = (A(1 - \cos\varphi)$ and

$$Nu_\psi = 0.81\left(\frac{\Phi_1}{d}\right)^{0.5} Pe^{0.5}\left[\frac{\sin\psi + \sin^2\psi}{1+\sin^2\psi}\right]^{0.5} \tag{3}$$

for q = const. The experimental formulas of [5] are:

$$Nu_\psi = \left(\frac{\Phi_1}{d}\right)^{0.5}\left(\frac{S-d}{S}\right)^{0.5}\left[\frac{\sin\psi + \sin^2\psi}{1+\sin^2\psi}\right]^{0.5}[5.44 + 0.228\, Pe_{node}^{0.614}] \tag{4}$$

for $t_{ts} = A(1 - \cos\varphi)$ and

$$Nu_\psi = \left(\frac{\Phi_1}{d}\right)^{0.5}\left(\frac{S-d}{S}\right)^{0.5}\left[\frac{\sin\psi + \sin^2\psi}{1+\sin^2\psi}\right]^{0.5}[4.6 + 0.193\, Pe_{node}^{0.614}] \tag{5}$$

for q = const, and lie much lower than the obtained results, the discrepancy increasing with increasing Pe in the investigated range.

On the basis of this investigation we can recommend the following formula for the calculation of the heat exchange of bundles of tubes inclined at an angle ($90° \geq \psi \geq 30°$) to the incoming flow of a liquid-metal heat-transfer agent ($0.007 \leq Pr \leq 0.03$) in the Peclet number range Pe = 10-600:

$$Nu_\psi = \sin^{0.4}\psi\, Nu_{90},$$

which has a simpler structure than formulas (2) and (3).

NOTATION

S	is the distance between tube centers;
d	is the external diameter of tubes;
ψ	is the angle of tube inclination to flow direction;
w	is the velocity of incoming heat-transfer-agent flow;
V	is the heat-transfer-agent flow rate;
Ω	is the cross section of box;
Φ_1	is the single hydrodynamic potential near frontal point;
φ	is the angle over the tube-bundle circumference calculated from frontal point;
q	is the heat flux through the tube surface;
t_{ts}	is the temperature of tube surface;
$Pe = wd/a$	is the Peclet number.
$Nu = \alpha d/\lambda$	is the Nusselt number.

LITERATURE CITED

1. V. M. Borishanskii, S. S. Kutateladze, V. L. Lel'chuka, and I. I. Novikov (editors), Liquid Metals [in Russian], Atomizdat (1963).
2. P. L. Kirillov, V. I. Subbotina, and P. A. Ushakov (editors), Liquid Metals [in Russian], Atomizdat (1967).

3. O. E. Dwyer, "Recent developments in liquid-metal heat transfer," Atom. Energy, Rev. 4, 3 (1966).
4. Chia Jung Hsu, Int. J. Heat Mass Transfer, 8, 303 (1965).
5. Sh. Kalish and O. E. Dwyer, Int. J. Heat Mass Transfer, 10, 1533 (1967).
6. V. M. Borishanskii, A. A. Andreevskii, V. B. Zhinkina, and L. L. Shneiderman, in: Liquid Metals [in Russian], Gosatomizdat (1963), p. 183.
7. V. M. Borishanskii, V. B. Zhinkina, and E. V. Firsova, Proceedings of the Central Boiler and Turbine Institute [in Russian], No. 86 (1968).