5. K. Stepman, "Heat transfer in boiling mixtures," Seventh Int. Heat Transfer Conf., Vol. 1, Munich (1982), pp. 71-76.
6. Yu. A. Kuzma-Kichta, I. V. Livanov, V. N. Moskvin, et al., "Study of heat transfer during the boiling of water with the addition of surfactants in a broad pressure range," Teploenergetika, No. 2, 60-61 (1982).
7. V. V. Yagov, A. K. Gorodov, and D. A. Labuntsov, "Experimental study of heat transfer during the boiling of liquids in a vacuum under conditions of free motion," in: Documents of a Scientific—Technical Conference on the Results of Scientific-Research Projects for 1968-1969. Section "Industrial Heat and Power Engineering," Subsection "Dryers and Heat Exchangers," Moscow Power Engineering Institute (1969), pp. 131-145.
8. B. P. Avksentyuk, "Nucleate boiling," Inzh.-Fiz. Zh., 40, No. 3, 394-401 (1981).
9. S. S. Kutateladze, Principles of the Theory of Heat Exchange [in Russian], Atomizdat, Moscow (1979).

STUDY OF FLOW ON THE SURFACE OF FINS ON CROSS-FINNED TUBES

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The visualization method was used to study the washing of a flow of air over the surface of fins on tubes with external fins in an annular arrangement.

There has been far too little study of the hydrodynamics of flow about cross-finned tubes, which determines the laws governing local and surface-mean heat exchange. This article attempts to study flow on the surface of fins in a staggered bundle of cross-washed tubes with external annular finning by visualizing it in a soot—kerosine suspension. The results of our observations, reported below, pertain mainly to the first row of the bundle. This permits the data to be compared with adequate accuracy to well-known data on the distribution of local heat-transfer coefficients on the surface of annular fins [1, 2]. Two types of completely turned steel tubes differing in the height of the fins were used to make up a bundle with the spacing characteristics S_1 = 84 mm and S_2 = 200 mm. The main dimensions of the finned tubes are shown in Table 1. The experiments were conducted in an open wind tunnel with a through part having a cross section of 71 × 334 mm. The tubes used for the visualization had a joint at the middle of their height. The ends mated to one another at the joint were polished and coated with white nitrocellulose enamel.

During the tests the surface of the fin below the joint was coated with a thin layer of the soot—kerosine suspension. Then both halves of the tube were joined together and the tube was placed in the working part of the stand. Here, it was held in an isothermal air flow. The flow, interacting with the suspension film, was compelled to move in streamlines and formed a flow pattern in the form of streaks and points. Over time the kerosine evaporated and the soot particles remained at the locations on the tube surface to which they had been moved while in the suspended state. The thus-obtained images of the surface had lighter sections corresponding to zones of the surface that had been washed by the flow with the most intensity. Zones with zero velocity or a slight circulating motion appeared as dark spots or bands.

Figures 1 and 2 show photographs illustrating results of the tests. Study of the photographs made it possible to establish several features of flow about the fins.

The forcing of the flow out of the interfin channel is evident. This is related to an increase in the thickness of the boundary layer on the fin, so that the streamlines are below the midsection (Fig. 1a and c, and Fig. 2a and c) and the contours of the vortical aft zone beyond the tube (Fig. 2b) diverge from the longitudinal axis of the picture and have a curvature inverse to that which is typical of transverse flow over a smooth cylinder.

The dark band at the front edge of the fin (Fig. 1a) is evidently the result of flow separation beyond the sharp inlet edge, the presence of this band having been noted in works

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TABLE 1. Geometric Characteristics of the Finned Tubes

Type of tube	d, mm	h, mm	t, mm	δ, mm	ψ
1	21,0	30,0	4,0	1,2	38,32
2	21,0	18,0	4,0	1,2	18,25

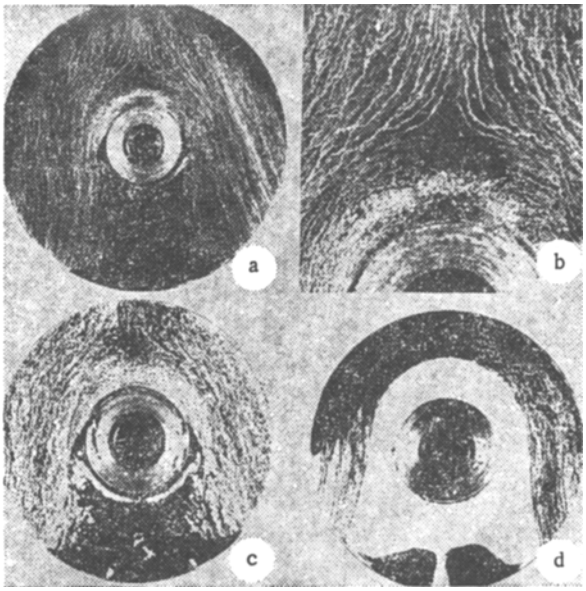

Fig. 1. Flow on the surface of fins in the first row of the staggered bundle S_1 = 84 mm, S_2 = 200 mm; a) tube of type 1, Re = $1.52 \cdot 10^4$; b) tube of type 1, section of fin ahead of front part of finned tube, Re = $1.52 \cdot 10^4$; c) tube of type 2, Re = $1.71 \cdot 10^4$; d) tube of type 2, result of experiment to determine the position of the boundary of the separation zone A, Re = $1.71 \cdot 10^4$.

on local heat transfer [1, 2]. However, we did not see systematic evidence of such separation.

A zone with an outer boundary close to a circle arc (Fig. 1b) is located near the front semicircle of the finned tube, the streamlines bisecting ahead of this zone. The zone (we will refer to it as zone A) has a complicated structure and generally consists of two dark concave bands and one lighter concave band. The first dark band, fairly narrow and not always distinct, is located directly on the finned tube. Then follows a broader and generally lighter band consisting of a collection of light streaks counter to the main flow of soot particles. The second dark band, being the outer boundary of the zone, is compressed with increasing distance from the long axis of the picture. Photographs showing the flow pattern at relatively low velocities illustrate that the widest part of this band has the appearance of a dark rhomboid spot enclosed between diversing streamlines.

The reasons for the formation of zone A are connected with the three-dimensional nature of the flow at the base of the fin (Fig. 3). Due to the difference in velocities near the fin surface and in the core of the interfin cavity — related to the formation of the boundary layer — when the flow strikes the wall of the finned tube a pressure gradient is created along the OZ axis. This gradient in turn causes air to move from the center of the interfin channel to the bases of the fins. The consequent secondary flow attaches to the fin surface on section A_2, forming a small angular separation region A_1. This region is visible on the photograph as the first dark band in zone A. The attachment section A_2 corresponds to the light band in the photograph. Flow within this section can be characterized as being counter to the main flow. The flow separates from the fin surface when the secondary and main flows

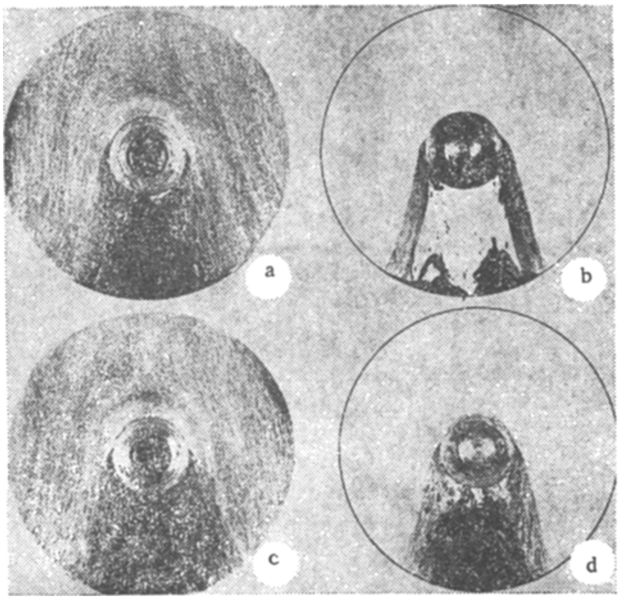

Fig. 2. Results of experiment in the first and third rows of the staggered bundle S_1 = 84 mm, S_2 = 200 mm, tube of type 1, Re = $3.32 \cdot 10^4$; a) flow on a fin in the first row; b, d) wake on the fin opposite the fin coated with the soot–kerosine suspension, in the first and third rows, respectively; c) flow on a fin in the third row.

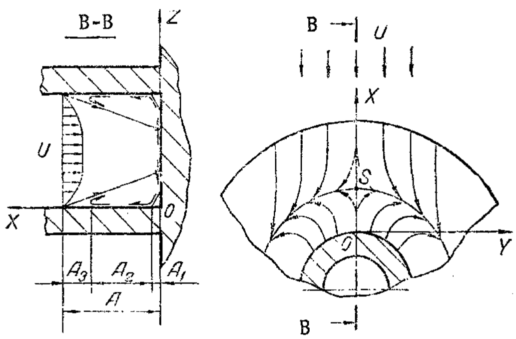

Fig. 3. Diagram of flow ahead of front part of bearing tube.

meet. The separation section A_3 is visible in the photograph as the outer dark band of zone A. Lying at the center of the latter is singular separation point S. This point is the critical point for both the main and the secondary flows in the XOY plane. The velocity of the flow around this point is no longer great enough to move the soot particles, which are then deposited in the form of the dark rhomboid spot. The flow separated from the fin reattaches itself to the wall of the finned tube and again begins to move toward the base of the fin, forming a separated circulation zone. However, this circulation zone is not closed, and outflow occurs in the lateral directions. The secondary flows continuously transfer momentum from the core of the interfin flow to the aft zones and thus here cause a substantial increase in velocity (and, hence, local heat transfer), as is evidenced by the lightness of most of zone A.

To refine the position of the boundary of the zone and to study the dependence of its size x_{0S} on the OX axis on the Reynolds number, we conducted a series of tests in which the soot–kerosine suspension was applied only to a narrow strip along the front end of the fin rather than over its entire surface. As a result, after the tube was inserted in the air flow, the sections washed by the secondary flow remained undarkened because the soot particles entrained by the main flow could not cross the separation line. Figure 1d shows the

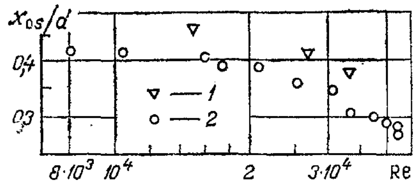

Fig. 4. Dependence of the relative size x_{os}/d of zone A on the Reynolds number: 1) type 1 tube; 2) type 2 tube.

result of this experiment together with a photograph obtained at the same Re after complete coloring of the fin (Fig. 1c). The test data $x_{os}/d = f(\mathrm{Re})$ is shown in Fig. 4, from which it follows that an increase in the Reynolds number, beginning with $\mathrm{Re} \approx 1.5 \cdot 10^4$, leads to a decrease in the dimensions of the zone. A reduction in the height of the fin also leads to a decrease in the size of zone A, but in this case the percentage of its surface occupied by the zone increases — which is evident from the change in the ratio of x_{os} to the fin height h. For example, with $\mathrm{Re} = 1.5 \cdot 10^4$, the ratio x_{os}/h is about 0.3 for a type 1 tube and about 0.5 for a type 2 tube.

The foregoing suggests that the separation zone ahead of the front part of the finned tube may exist at any fin height which is sufficient to form a hydrodynamic boundary layer on its surface. The spacing between the fins, within the commercially practicable range, should not significantly affect the mechanism of formation and dimensions of the separation zone.

The flow features in zone A make it possible to explain the character of the distribution of the heat-transfer coefficients on the corresponding fin sections [1, 2]. In particular, the lightest part of zone A, on the section where the secondary flow attaches itself to the fin surface at its base, is evidence of a high flow rate and explains the presence of the heat-transfer maximum, mentioned in the other studies, at this site. The site of flow separation on the outer boundary of zone A corresponds to the reductions in heat-transfer coefficient noted in [1, 2] over the entire front semicircle of the fin.

Flow and heat transfer in zones similar to those described above were studied in [3, 4] for the case of their formation ahead of cylindrical projections on a plate. However, except for [1], none of the well-known publications devoted to heat transfer and flow over finned tubes contain any information on this phenomenon. This includes the relatively recent [5, 6]. The authors of [1] mention the existence of a horseshoe-shaped vortex ahead of the bearing cylinder. Quite the contrary, the studies [7-9] and other investigations report the presence of stagnation zones at the bases of the interfin cavities. These zones were connected with the enveloping of the bearing tube and the root parts of the fins by the thickened boundary layer and the consequent isolation of part of the surface from active heat exchange — a situation which, in our opinion, does not conform to the reality.

Judging from Fig. 1a and c, and Fig. 2a, in the aft part of the fin lying in the wind shadow of the bearing tube reduced velocities are combined with substantial vorticity. As was already noted, only the fin below the joint was covered with the soot–kerosine suspension during the tests. This allowed us to observe zones of intensive three-dimensional perturbations on the boundaries of the wake beyond the bearing cylinder. These zones were judged to be present on the basis of the two narrow bands appearing on the adjacent clean fin (Fig. 2b), the bands having been formed as a result of lateral transport of the suspension from the surface on which it was originally deposited (a and b in Fig. 2 were obtained in one experiment). The appearance of these narrow, distinct zones should evidently by considered a phenomenon specific to the case of flow over cross-finned tubes and should be considered related to the separation from the bearing cylinder of boundary layers subjected to the action of circulation flows which form, as noted above, in zone A and propagate downstream.

The zones of intensive three-dimensional perturbations correspond to narrow sections of increased heat transfer on the boundaries of the aft region, distinguished in α-distributions [1, 2]. Located between them is a zone with fine vortical structures characterized by weak recirculatory motion and, accordingly, low heat transfer. Near the edge of the fin this zone becomes a region of large-scale vortices, a development associated with some increase in heat transfer at the rear edge of the fin in [1, 2]. The experiments showed that the vortex region approaches the wall of the finned tube with an increase in Re, which should lead to some equalization of heat transfer over the fin.

When the experimental tube is moved from the first to the third row of the bundle, the main changes in the flow pattern occur in the aft zone (Fig. 2c and d), where the large-scale vortices nearly reach the bearing tube. This reduces the size of the zone of weak recirculation flow to a minimum, a development which, as in the case examined above, should be accompanied by equalization of heat transfer over the fin. Visible on the photographs are sites of nucleation of vortices and vortex streets formed with their subsequent periodic separation and entrainment downstream. The symmetry of the wake is connected with the averaging of the flow pattern after a substantial period of time. However, it should be remembered that the flow conditions in the deeper rows of the bundle depend significantly on the parameters of the tube arrangement, which were left constant in our study.

The results of the above investigation make it possible to reach a conclusion on the unsubstantiated nature of the models of flow on the surface of cross-finned tubes constructed by analogy with flow over a smooth cylinder. It is also evident that the decrease in the surface-mean heat-transfer rate on finned tubes which accompanies an increase in the degree of finning is connected with the formation of stagnant zones at the roots of the fins.

NOTATION

S_1, transverse spacing of tubes in bundle; S_2, lengthwise spacing of tubes in bundle; d, diameter of tube bearing the fins; h, fin height; t, fin spacing; δ, fin thickness; ψ, finning coefficient; Re, Reynolds number calculated from the velocity of the incoming flow U and the diameter d; x_{0s}, size of the separation zone A on the OX axis; α, heat-transfer coefficient.

LITERATURE CITED

1. W. Krückels and V. Kottke, "Untersuchung über die Verteilung des Wärmeubergangs an Rippen und Rippenrohr-Modellen," Chem. Ing. Tech., 42, No. 6, 355-362 (1970).
2. V. M. Legkii, Ya. S. Zholudov, and O. A. Gerashchenko, "Local heat transfer on a single cross-washed circular tube with annular finning," Inzh.-Fiz. Zh., 30, No. 2, 274-280 (1976).
3. B. E. Luzhanskii and V. P. Solntsev, "Experimental study of flow in three-dimensional separation zones ahead of projections," Zh. Prikl. Mekh. Tekh. Fiz., No. 1, 50-54 (1972).
4. B. E. Luzhanskii and V. P. Solntsev, "Experimental study of heat transfer in separation zones ahead of cylindrical projections," Zh. Prikl. Mekh. Tekh. Fiz., No. 6, 83-89 (1972).
5. V. F. Yudin, Heat Exchange on Cross-Finned Tubes [in Russian], Mashinostroenie, Leningrad (1982).
6. R. M. Petrichenko, V. D. Krasil'nikov, V. D. Perch, and M. D. Chil'dinov, "Mathematical model of convective heat transfer on finned surfaces," Energomashinostroenie, No. 10, 18-20 (1978).
7. H. Brauer, "Wärme- und Stromungstechnische Untersuchungen an quer angeströmten Rippenrohrbündel," Chem. Ing. Tech., 33, No. 6, 431-438 (1961).
8. V. M. Antuf'ev, Efficiency of Different Shapes of Convective Heating Surfaces [in Russian], Énergiya, Moscow-Leningrad (1966), p. 116.
9. I. G. Taranyan, F. M. Iokhvedov, and V. B. Kuntysh, "Study of the effect of finning parameters on the heat transfer and resistance of staggered bundles of tubes with transverse smooth and integral fins," Teplofiz. Vys. Temp., 10, No. 5, 1049-1054 (1972).