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Heat transfer enhancement at tubular transversely finned heating surfaces

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ABSTRACT

A review of the methods of heat transfer enhancement in transversely finned tubes is made. Two types of enhanced heat transfer surfaces – tubes with fins bent in the form of a confuser and flat-oval tubes with incomplete finning are proposed. The results for heat transfer and drag of such surfaces by varying geometric and performance characteristics are presented. It is shown that the use of the surfaces of the proposed types enables one to substantially decrease the metal content and sizes of heat transfer equipment.

1. Current state of the problem

The problem of improving heat transfer surfaces shaped as transversely finned tube bundles is highly relevant today. The study of the available works on this problem has shown that the ways to enhance heat transfer at transversely finned surfaces are mainly associated with the search for the most efficient shapes of finning and arrangement of finned tube bundles.

A great number of developments of enhanced heat transfer surfaces are concerned with creating conditions for separation of thickened boundary layers on relatively high fins and for organization of developed vortex flow possibly over the entire surface. Such conditions are attained due to the corrugation of transverse fins [1], their perforation [2,3], their cutting into short sections with ends bent in different directions [4–8], as well as due to the use of the so-called segment finning [9].

The analysis of these developments and related research makes it possible to emphasize the following. The use of corrugated fins causes heat transfer to enhance significantly. In this case, heat transfer enhancement is accompanied by an even more noticeable growth of aerodynamic drag. According to the data [1], replacing smooth fins by corrugated ones on a single finned tube at $Re = 10^4$ results in the heat transfer enhancement by 12%,…,15% with increasing the drag by 65%,…,70%. This fact in combination with the low manufacturability of tubes with corrugated fins makes their wide application problematic.

The results on the thermal and hydraulic performance of bundles of tubes with cut fins [4–7] are broadly covered in the literature. Such heat transfer surfaces are made of tubes with conventional spiral finning when fins are cut into short sections by fine milling along the generatrix of the finned tube or in the spiral line at an angle of 45° to it. The cutting practically does not decrease the fin surface and allows one to enhance heat transfer by 12%,…,36% depending on finning parameters and on the way of cutting fins according to the above-mentioned works. The flow swirling effect to be created in this case is the more appreciable, the higher the fins to be cut. However in all cases the drag growth is well ahead of the heat transfer one, which as a whole significantly reduces the total effect of heat transfer enhancement. Moreover, the manufacture of tubes with cut fins needs additional technology, production floor spaces, and expenses. In combination with the high contamination of heat transfer surfaces manufactured of such tubes and with the difficulty of their cleaning, their use has been substantially restricted.

For close thermal and hydraulic performance values, the solution associated with making cuts on the rolled fin edges that swirl the flow [10–12] is most technologically justified. Because of this, it has found use in manufacturing heat transfer surfaces of aluminum tubes for some types of air cooling devices. However in addition to the limited application of temperature conditions, this solution preserved substantial operational disadvantages of cut fins with bent edges – elevated contamination and difficulties in

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Nomenclature

A	area of the outer surfaces of a finned tube
A_f	surface area of fins
A_t	surface area of the supporting tube unoccupied with fins
b	bending degree of fins
b_s	petal width of a segment fin
d	diameter of a tube with finning
d_1	transverse size of the cross section of a flat-oval tube
d_2	longitudinal size of the cross section of a flat-oval tube
E	fin efficiency
Eu_0	Euler number based on one transverse row of a bundle
G	mass flowrate of heat carrier
h	fin height
h_s	petal height of a segment fin
Nu	Nusselt number
Q	heat power of heat exchanger
ΔP	pressure drop
Re	Reynolds number
Re_{fs}	Reynolds number calculated in terms of incoming flow velocity
S_1	transverse pitch of tubes in a bundle
S_2	longitudinal pitch of tubes in a bundle
t	fin pitch
U	flow velocity
z_2	number of transverse rows of tubes in a bundle

Greek symbols

$\bar{\alpha}$	average heat transfer coefficient
α_i	fin height-averaged heat transfer coefficient
$\bar{\alpha}_{\text{red}}$	reduced heat transfer coefficient
γ	angle of confuser-type bending of a fin
δ	thickness of a fin
ξ_0	drag coefficient based on to one row of a bundle
θ_h	attack angle of a fin
θ_p	attack angle of a flat-oval tube
σ_1	relative transverse pitch of tubes in a bundle
σ_2	relative longitudinal pitch of tubes in a bundle
ψ	finning coefficient

cleaning interfin spaces that are being aggravated because these spaces are much blocked with deformed fin edges [12].

The type of finning called the segment one in the literature [9] has gained enough popularity. Tubes with such finning (Fig. 1) can be produced on the same equipment as those with conventional spiral fins by high-frequency current welding of a punched steel ribbon to a tube. Owing to great interest in segment-finned surfaces expressed by power machine-building companies and owing to the non-high accuracy of the available computational methods [9], experimental studies were made of heat transfer, aerodynamic drag, and features of flow around such surfaces [13–16] at the NTUU "KPI". Experiments on bundles ($\sigma_1/\sigma_2 = 0.8,\ldots,2.5$) of natural staggered and in-line tubes ($d = 32,\ldots,42$ mm, $h = 11.5,\ldots,19.5$ mm, $b_s = 4.0$ mm, $h_s = 5.8,\ldots,12.5$ mm, $t = 5,\ldots,10$ mm, $\psi = 4.6,\ldots,10.4$) showed that the replacement of conventional spiral finning by segment one enables a number of tubes in a bundle to be decreased by a factor of 18%,…,20% under other things being equal. The formulas for calculation of surface-averaged heat transfer and drag of segment-finned tube bundles mainly preserve the structure of the corresponding formulas for tubes with conventional spiral finning [17].

It is obvious that heat transfer in segment-finned tube bundles is enhanced due to a small boundary layer thickness on narrow petals and due to flow swirling when the flow is separated from a developed sharp fin edge and also when each element (petal) of a segment fin is in essence a forward rectangular fin, whose efficiency coefficient is, as known, higher than that of an orifice one. The flow visualization on the segment-finned surface (Fig. 1) [16] has shown that when the basic features of the flow pattern specific for a conventional orifice fin are preserved [18], on the segment fin due to the above-mentioned additional flow swirling the points of its separation from the finned tube much displace downstream – the more swirled flow is able of moving downstream in the stern zone against the positive pressure gradient. As a result, the sizes of the vortex zone characteristic for a weak recirculation flow in its larger part significantly decrease. This zone acquires a tapered shape downstream and the length of vortex braids at its side boundaries increases within the fin. Finally, surface-averaged heat transfer is enhanced. The investigations carried out at the NTUU "KPI" also showed that the thermal and hydraulic performance of segment-finned tube bundles is possible by rotating petals around its longitudinal axis [13].

Among the developments made is the transverse finning with perforation [2], as well as such its exotic diversity as K–Y-finning [3]. As the investigations [2] showed, the steel tubes with perforated rectangular fins have the thermal and hydraulic performance that practically does not differ from that of tubes with conventional orifice finning. K–Y-finning is characteristic for high aerodynamic drag, which in combination with its small strength and the absence of a reliable thermal contact with a carrying tube due to a particular manufacturing technology restricts the field of their application.

The heat transfer enhancement method elsewhere outlined in [19] is also associated with perforating a thin fin. Its essence means that two small delta-shaped wings representing bent parts of a perforated fin are formed on the rectangular fin behind the finned tube. The wings inclined towards the incoming flow generate longitudinal vortices that enhance heat transfer in the wall region. To the opinion of the present authors, when applied to real heat exchangers this may enhance heat transfer by 20% and reduce operating costs by 10%.

$$\frac{h}{d} = 0.44; \ \frac{h5}{d} = 0.28; \ Re = 2.2 \times 10^4$$

In Refs. [20,21], the improvement of weight and dimensions of surfaces produced from round tubes with spiral rolled finning means that some part of finning being in the wake region behind the finned tube is removed. As known, the heat transfer intensity as a whole is relatively not high here. In order that the process of removing some part of finning should be possibly more technological, the authors propose to cut off fins on the chord along the plane parallel to the tube mid-section (Fig. 2). According to the data [20,21], the heat transfer coefficients based on a total surface of such tubes increase in comparison with conventional finned tubes by a factor of 1.23 at $Re = 3 \times 10^3$ and by a factor of 1.13 at $Re = 2.5 \times 10^4$. Aerodynamic drag in this case practically does not change. However the total heat removal by reducing the heat-release surface decreases by 13% and 23%, respectively. Nevertheless, the authors argue that up to 28% of metal spent for finning production can thus be saved under other things being equal. As a whole, the considered way of improving transversely finned surfaces cannot be recognized rational for obvious reasons.

A search for new arrangement types of finned tubes in bundles is one more direction of improving the thermal and hydraulic