Research of heat transfer of staggered horizontal bundles of finned tubes at free air convection

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Abstract. The study of free-convective processes is important because of the cooling problem in many machines and systems, where other ways of cooling are impossible or impractical. Natural convective processes are common in the steam turbine air condensers of electric power plants located within the city limits, in dry cooling towers of circulating water systems, in condensers cooled by air and water, in radiators cooling oil of power electric transformers, in emergency cooling systems of nuclear reactors, in solar power, as well as in air-cooling of power semiconductor energy converters. All this makes actual the synthesis of the results of theoretical and experimental research of free convection for heat exchangers with finned tube bundles. The results of the study of free-convection heat transfer for two-, three- and four-row staggered horizontal bundles of industrial bimetallic finned tubes with finning factor of 16.8 and equilateral tubes arrangement are presented. Cross and diagonal steps in the bundles are the same: 58; 61; 64; 70; 76; 86; 100 mm, which corresponds to the relative steps: 1.042; 1.096; 1.152; 1.258; 1.366; 1.545; 1.797. These steps are standardized for air coolers. An equation for calculating the free-convection heat transfer, taking into account the influence of geometrical parameters in the range of Rayleigh number from 30,000 to 350,000 with an average deviation of ± 4.8%, has been obtained. The relationship presented in the article allows designing a wide range of air coolers for various applications, working in the free convection modes.

1. Introduction

Application of free-convective processes in power units and installations with developed heating surfaces have increased significantly nowadays: steam turbine air condensers of electric power plants, dry cooling towers of circulating water systems for enterprises, solar energy, etc. [1–3]. But the practical realization of the natural convective processes is constrained by insufficient knowledge. There are criterial equations for the free-convective heat transfer of smooth-tube heating surfaces, single finned cylinders and single-row ribbed bundles in the scientific and technical literature, which cover the required range by changing the geometric parameters of tubes and bundles [4–6]. The existing criterial equations work in a narrow range of bundle types, but there is no common opinion about the characteristic size and the determining temperature, in most cases the radiant component is not taken into account, which leads to a heterogeneity in the numerical values of the heat transfer coefficients. Studies of industrial designs of bimetallic finned tubes (BFT) are even more limited [7]. All this makes the actual synthesis of the results of theoretical and experimental research of free convection on finned heating surfaces actual with industrial BFT. Scheme of the experimental device for conducting heat transfer research for natural air convection, test procedure and the data processing technique are given in [8, 9].
2. Research plant and experiments

2.1 The results of an experimental research of the natural-convective heat transfer of staggered bundles

The research of natural-convective heat transfer of experimental models of two-row, three-row, four-row staggered bundles made of BFT with fining factor of $\varphi = 16.8$ was carried out. The tube spacing was equilateral and cross and diagonal steps in the bundles were the same: $S_1 = \frac{S_2}{2} = 58; 61; 64; 70; 76; 86; 100$ mm, which corresponds to the relative steps $\alpha_1 = \frac{S_1}{d} = \alpha_2 = \frac{S_2}{d} = 1.042; 1.096; 1.150; 1.258; 1.366; 1.545; 1.797$. The longitudinal step of the tube spacing was equal to $S_2 = 0.866 \cdot S_1 = 50.2; 52.8; 55.4; 60.6; 65.8; 74.5; 86.6$ mm, which corresponds to the relative step $\alpha_2 = \frac{S_2}{d} = 0.903; 0.949; 0.996; 1.089; 1.183; 1.338; 1.556$.

The results of the experiments on the average heat transfer of two-, three- and four-row bundles are graphically presented in Figure 1.

The interval of the obtained values of the average natural convective heat transfer coefficients of the two-row bundles $a_{1o} = 0.51 \ldots 2.9$ W/(m$^2$·K), three-row bundles $a_{2o} = 0.43 \ldots 2.8$ W/(m$^2$·K), four-row bundles $a_{3o} = 0.32 \ldots 2.9$ W/(m$^2$·K). Heat transfer by radiation was $15 \ldots 30\%$ from the total heat flux for two-row bundles and $10 \ldots 25\%$ from the total heat flux for three- and four-row bundles due to reradiating. The maximum range changing of the Rayleigh number for two-row bundles $Ra = (0.3 \ldots 4.0) \cdot 10^3$, and for three- and four-row bundles $Ra = (0.3 \ldots 4.0) \cdot 10^5$.

When analyzing the graphs it is clearly seen that for two-row bundles in the interval of steps $1.042 < \alpha_1 < 1.258$ the average heat transfer increases rapidly. This is due to an increase of the relative cross-section area, in which the air flow accelerates with increasing tube step. Subsequent increase of step from $1.258$ to $1.797$ slightly affects the heat transfer of the BFT. An implicit maximum can be observed at the step $\alpha_1 = 1.545$. To analyze the effect of step $\alpha_1$ with a constant number $Ra = 150,000$, $\alpha_1 = 1.042$ was taken as a basic step. As the step increases, the increase in heat transfer takes place: at the step $1.096$ by $23\%$, at $1.150$ – by $28\%$, at $1.258$ – by $43\%$, at the steps $1.366$ and $1.797$ – by $44\%$, at $1.545$ – by $46\%$.

For three-row bundles in the interval of steps $1.042 < \alpha_1 < 1.50$, the average heat transfer of the bundles is substantially increased. This phenomenon, as in double-row bundles, is due to an increase in the relative cross-section area, in which the air flow accelerates with increasing step of the tubes. The subsequent increase in the step from $1.150$ to $1.366$ has minimal impact on the heat transfer growth rate of the BFT. In the range from $1.366$ to $1.797$, the average heat transfer remains practically unchanged. Comparison of the heat transfer values of the three-row bundles relative to the $1.042$ step with the Rayleigh number $Ra = 1.5 \cdot 10^5$ is: at the step of $1.096$ more by $22\%$, at $1.150$ – by $41\%$, at $1.258$ – by $52\%$, at $1.366$ and $1.545$ – by $55\%$, at $1.797$ – by $57\%$.

For four-row bundles in the interval of steps $1.042 < \alpha_1 < 1.258$, the average heat transfer of the bundles is substantially increased, because there is an effect of the discharge shaft, arising from increased air flow acceleration due to lower aerodynamic drag and from decrease in the air density along the bundle height. At the step size from $1.258$ to $1.797$, the heat transfer rate decreases. In this case, the maximum heat transfer at the step of $\alpha_1 = 1.797$ is seen. Values of the bundles heat transfer for a constant value of the Rayleigh number $Ra = 1.5 \cdot 10^5$ were compared with the step of $1.042$, which already has a heat transfer of more by $28\%$ at the step of $1.096$, at $1.150$ – by $44\%$, at $1.258$ – by $59\%$, at $1.366$ – by $64\%$, at $1.545$ – by $67\%$, at $1.797$ – by $70\%$. 


The experimental points for each series of experiments on the average heat transfer with an average deviation of no more \( \pm 4\% \) are averaged by a formula:

\[
\text{Nu} = A \cdot \text{Ra}^n.
\]  

The values of the coefficients \( A \) and \( n \), and ranges of applicability according to the Rayleigh number \( \text{Ra} \) are given at the Table 1.

According to Table 1, it can be concluded that the exponent \( n \) of all steps deviates from the average by no more than 3 \% for two- and four-row bundles and by 4.5 \% for three-row bundles. This may mean the same nature of the air flow in the intertubular space, indicates the constancy of the air flow pattern and confirms the similarity of the bundles aerodynamics.

**Figure 1.** Average heat transfer of bundles: 1-7 - relative steps \( \sigma_1 = 1.042; 1.096; 1.15; 1.258; 1.366; 1.545; 1.797 \) respectively; I, II, III - two-, three-, four-row bundles, respectively.
2.2 Analysis of heat transfer of tube bundles depending on the number of rows and step.

The number of bundle rows affects the acceleration of the air flow caused by a smaller air heating in the small-row bundles, and less pronounced effect of the adjacent tubes boundary layers.

Analyzing the change in the heat transfer rate for each step (Figure 2) with a change in the rows number, it can be concluded that with an increase in the step from 1.042 to 1.258, the decrease in the heat transfer of the bundle is clearly seen with increasing number of rows due to the increase in its aerodynamic resistance and the effect of an air flow with a higher temperature, which warmed up in the lower rows of tubes. In the range of steps 1.258 ÷ 1.545, the difference in heat transfer is lost. This confirms that the change in the air flow cross section affects the heat transfer coefficient. In turn, the greater the number of rows and the freer step of the tubes, the more intense the effect of the acceleration of the air flow, because the lift increases due to the difference in density, and the resistance to movement decreases. This effect helps to achieve greater total heat transfer in sparse bundles.

3. Results and discussion

3.1 Derivation of the generalization equation.

In the derivation of the generalization equation covering 224 experimental points, we proceeded from the condition that the number Nu is a function of the Rayleigh number and the basic geometric parameters of the bundle:

$$\text{Nu} = f(\sigma_1, \sigma, \text{Ra}).$$

(2)

The analysis showed that the effect of the relative step $\sigma_1$ is complex: in the range from 1.042 to 1.258, the slope of the curve is steeper than for the range from 1.258 to 1.797. Therefore, it was proposed to obtain a generalizing formula separately for close and for rarefied bundles. The geometry of the bundle is characterized by power law dependence. The processing of the experimental data by the dependence (2) was carried out in the Excel (search for a solution). The main criterion in determining the influence of geometric parameters of bundle was the minimum of the mean deviation between the experimental and calculated values of the number Nu. As a result, the following dependencies were obtained.

For $\sigma_1 = 1.042...1.258$:

$$\text{Nu} = 0.0135 \cdot \sigma_1^{1.8205} \cdot z^{-0.287} \cdot \text{Ra}^{0.369}.$$  

(3)
Figure 2. Heat transfer of staggered tube banks in steps of $\sigma_1 = 1.042 \ldots 1.797$. 
The average deviation is ± 8.9 %, the maximum deviation is 25 %. Area of application: Ra = 33,500 ... 370,000; \( \sigma_1 = 1.042 \ldots 1.258 \); \( z = 2, 3, 4 \).

For \( \sigma_1 = 1.258 \ldots 1.797 \):

\[
Nu = 0.0317 \cdot \sigma_1^{0.264} \cdot z^{-0.287} \cdot Ra^{0.369}.
\] (4)

The average deviation is ± 5.4 %, the maximum – 16 %. Application area: Ra = 27,000 ... 390,000; \( \sigma_1 = 1.258 \ldots 1.797 \); \( z = 2, 3, 4 \).

4. Conclusions

In conclusion, it should be noted that the obtained equations (3) and (4) can be used in practical calculations with a sufficient degree of accuracy.

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