The influence of heat transfer fluid temperature on optimal characteristics of the heating convector

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Abstract. Heat transfer of a finned heating convector into a heated room is considered at different input heat transfer fluid temperature levels. It is shown that with decreasing heat transfer fluid temperature, a maximum ratio of heat flux per unit length of the heating convector to its weight \( Q/m \) is achieved with a larger distance between the fins. It allows saving metal in manufacturing the finned heating convectors, which is widely used in low-temperature heating systems.

1. Introduction
Recently, the energy saving by using low-temperature heat transfer fluids in heating systems has become extremely important [1]. These fluids can be obtained in condensation boilers or utilization heat exchangers using the heat of by-products of various technological processes in industry. According to estimates, the decrease of heat transfer fluid temperature may be expected in the near future due to the shift to alternative heating systems with non-traditional renewable energy sources [1]. Within this context, it is very important to develop the efficient heating units using low-temperature heat transfer fluids. The use of heating convectors for these systems, which are already widely applied both in residential buildings and in social facilities, is being actively considered [2]. A point of great interest in the design of convectors is to reduce metal consumption for their manufacture and consequently save fuel and energy resources [3].

2. The mathematical model of convector heat transfer

Heating convector consists of one or more supportive pipes finned with flat plates. Heat from these plates is transferred mostly by natural convection and, in a lesser degree, by radiation. Recently, many papers [4-8] on the heat transfer from finned surfaces have been published.

The purpose of this paper is to define the influence of heat transfer fluid temperature on transmitted heat flux and optimal geometrical characteristics of heating convector. A ratio of convector transmitted heat flux to its weight \( Q/m \) is used as a target function. In the general case, additional conditions are imposed on the target function: a heat flux per unit length of a heating convector should be no less than value set by a consumer.

Earlier the mathematical model of convector heat transfer was developed by authors of [9]. This model considered both convective and radiation heat transfer.
The heating convector scheme with support pipe finned by round or square plates is shown in figure 1. The geometric parameters vary: the distance between fins (1-15 mm), fin thickness (1-10 mm) and fin height (10-50 mm). The calculations were made assuming that the basic fin temperature was equal to the heat transfer fluid temperature ($T_0$).

![Figure 1](image.png)

Figure 1. The scheme of heating convector with round and square fins: $D$ – round fin diameter ($a$ – fin height in the case of square fin), $d$ – pipe diameter, $b$ – the distance between fins, $L$ – the convector length, $n$ – number of fins, $\delta$ – fin thickness, $q_{cf}$, $q_{cf}$, $q_{cp}$, $q_{rp}$, $q_{ce}$, $q_{re}$ – convective and radiative heat transfer from the relevant surfaces: fin, pipe, fin end.

Initial calculations showed that convective heat transmitted by a finned pipe of a given length can be defined using the following approximate method. Instead of solving the heat equation at the fin [10], the known efficiency value of flat round or square fins is obtained from an analytical solution of this equation with an average heat transfer coefficient over the surface of the fin as in equation (1).

$$Q_{cf} = \bar{\alpha} \cdot (T_0 - T_{\infty}) \cdot \eta \cdot 2 \cdot F_i \cdot n$$

(1)

In this case, the heat transfer coefficient ($\bar{\alpha}$) was determined taking into account the decreasing distance between the fins when boundary layers are close and air velocity decreases on the surface between the fins, which leads to a strong reduction in heat transfer by convection. The reduction of the heat transfer coefficient at convective heat transfer with decreasing distance between the fins was performed using Elenbaas equation (2) from [11]:

$$Nu = \frac{1}{24} \cdot \frac{b}{a} \cdot Ra \cdot \left[1 - \exp \left(-35 \cdot \frac{a}{b \cdot Ra} \right) \right]^{3/4}$$

(2)

where $b$ is the distance between fins, $m$; and $Ra = Gr \cdot Pr$ is the Rayleigh number.

Considering the round fins, in equation (2) it is expedient to use the round fin diameter ($D$) with area equivalent to the square fin area with fin height ($a$) instead of $a$. To determine the efficiency of round fins, the approximation dependence equation (3) was used. It was proposed in [9] and verified by comparison with flat round fins efficiency value from numerical calculations.

$$\eta = \text{th} \left[ m \cdot l \cdot \left( \frac{D}{d} \right)^{1/3} \right] \left[ m \cdot l \cdot \left( \frac{D}{d} \right)^{1/3} \right]^{-1}$$

(3)

where $m = \left( \frac{2 \cdot \bar{\alpha}}{\lambda \cdot \delta} \right)^{1/2}$ is the dimensionless complex, $l = 0.5 \cdot (D - d)$ is the effective fin height, $m$.

Radiation heat transfer from fins’ surfaces to ambient medium in equation (4) was determined using the average temperature of the fin surface, as well as taking into account the angular coefficients of radiation in the system of surfaces: parallel vertical fins and ambient medium, by the Stefan-Boltzmann law [12]:

$$Q_{rf} = 2 \cdot \varepsilon \cdot \sigma \cdot \left( T_f^4 - T_{\infty}^4 \right) \cdot F_i \cdot n \cdot (1 - \varphi)$$

(4)
Radiation from one fin to another in a system of two parallel vertical fins was taken into account by angular coefficients of radiation according to the property of reciprocity ($\varphi_{12} = \varphi_{21}$), which was determined by [12]. The heat flux transferred by fin radiation to ambient medium was determined by taking into account the property of closure ($1 - \varphi_{12}$).

The calculations have shown that the radiation heat transfer is a significant part (more than 10%) of the total heat flux [13] transmitted by heating convector and has significant influence on the optimal distance between fins.

3. Results and discussion

Calculations have resulted in the dependence between the target function and the distance between fins for different heat transfer fluid temperatures, resented in figure 2.

With decreasing heat transfer fluid temperature the maximum of objective function is observed at larger distance between fins. It may be explained by an increase in the thickness of the boundary layers formed on the surfaces of the fins at low temperatures. Therefore, at small distances between the fins with lower temperature there is a more significant heat transfer decrease from their surface to the ambient environment. In this case, the mass of the convector could be reduced by increasing the distance between fins.

![Figure 2. The target function (Q/m) dependence on the distance between fins (b) for different heat transfer fluid temperatures ($T_0$).](image)

Figure 3 and 4 show the maximum value of the target function dependence (Q/m) and the optimal distance between fins on the heat transfer liquid temperature ($T_0$). The last dependence was received at fixed fin height (100 mm) and thickness values (1 mm) and the diameter of the supportive pipe (20 mm).

In the case of reviewed parameters, the calculations show (figure 3 and 4) that the contribution of radiation heat transfer to the total heat flux is 20-21% and cannot be neglected.

It can be seen in figure 4 that when using a low-temperature heat transfer fluid with the temperature of 45 °C, the optimal distance between fins is 12 mm, and at the assumed heat transfer fluid temperature (90 °C) for the convector the optimal distance is 10 mm.

An 8% increase in distance between fins can reduce the metal consumption of the convector by 3-5% depending on the diameter and wall thickness of the support pipe.
Figure 3. The target function \((Q/m)\) dependence on the heat transfer fluid temperature \((T_0)\): 1 – with radiation; 2 – without radiation.

Figure 4. The optimal fin spacing \((b)\) dependence on the heat transfer fluid temperature \((T_0)\): 1 – with radiation; 2 – without radiation.

Thus, when the heat transfer fluids of low temperatures are used in heating systems, the fins in the heating convectors should be installed at greater distance from each other.

Further, the target function will be optimized for the all geometric characteristics of the convector for various levels of heat transfer fluid temperature.

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