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Evaluation of the efficiency of aluminum ribbing in convector-type heating devices

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Abstract: The article is aimed at the theoretical and experimental evaluation of the thermal efficiency of aluminum ribbing of convector-type heating devices to improve indoor thermal comfort. The purpose of the manuscript is to increase the thermal efficiency of convector heaters with aluminum ribbing based on numerical modeling and obtaining analytical equations for determining the thermal parameters of convectors with aluminum ribbing, which is aimed at maintaining the proper microclimate in the room while ensuring energy savings. A chart of the dependence of the heat amount on the heat carrying medium flow rate, its initial and final temperature, was constructed. It was determined that the amount of heat increases if the flow rate of the heat carrying medium increases, its inlet temperature is increased and the outlet temperature is decreased.

Keywords: energy saving, indoor climate, heating system, convector, aluminum ribbing

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Introduction

Various factory-made heating devices are used in heating technology: steel ribbing convectors, cast iron and steel radiators, etc. Analyzing the advantages and disadvantages of these devices, it should be noted that despite the fact that cast iron radiators are quite effective in transferring heat, they are subject to quantitative and qualitative control, meet the requirements of energy conservation (Adamski, 2008; Dzierzgowski, 2021; Gumen et al., 2017; Lis & Ujma, 2017; Shapoval et al., 2017; Spodyniuk & Lis, 2021), but their cost is high. Convectors with round or rectangular steel ribbing are cheaper, but inferior to radiators in terms of heat output and cannot be controlled. The principle of their operation is to take advantage of the higher velocity of movement of the heat carrier to increase the heat transfer coefficients from the heat carrier to the pipe and from the pipe to the air, thus increasing the consumption of the heat carrier and increasing the diameter of the pipes. This factor, as well as the presence of a large area of steel ribbing, leads to a deterioration in resource efficiency. Based on the above, the idea of using aluminum ribbing in convectors emerged. It should be noted that in Ukraine and Poland there are developing the so-called “small enterprises” that conduct experimental production of various convector-type heating devices using aluminum ribbing (Voznyak et al., 2022). Such production requires scientific justification, determination of necessary parameters and their optimization.

Numerical modeling is one of the effective modern methods of scientific research (Antypov et al., 2021; Radulescu, 2018; Shayesteh & Fazeli, 2024). It has a number of advantages: lack of need for experimental testing saves the researcher’s time, the results of numerical modeling in the form of drawings are visually convenient, practical to use and allow to obtain hypothetical results.

1. Preliminary research and problem identification

The article presented here is continuation of the research (Voznyak et al., 2022). It is known that with room heating, the contribution of convection and radiation is different. For infrared heaters (Zhelykh et al., 2016) the contribution of radiation prevails, for radiant heaters the contributions are similar, and for convectors – the contribution of convection is greater. Convective heat transfer is determined using appropriate mathematical models (Adamski, 2013; Klymchuk, 2019) with a series of criterion equations (Voznyak et al., 2022). Usually, the choice of criterion equations depends on the mode of movement of the heat carrier, its thermophysical properties: thermal conductivity, specific heat, viscosity, etc., as well as convection conditions. These include the initial and final temperatures of the heat carrier, air, metal surfaces, heat carrier and air velocity, heat carrier consumption, room air temperature (Kapalo et al. 2018; 2020a; 2020b; Savchenko et al., 2023; Summa et al., 2024). Heating systems must ensure appropriate microclimate and thermal comfort conditions in rooms (Baldi et al., 2018; Ekim et al., 2023; Khovalyg et al., 2020; Lis, 2019; Zhao & Li, 2023).

In the presented paper, the given problem was solved theoretically, experimentally and numerically through modeling (Gorobets et al., 2021a) with further comparison of results. The k-ε model is widely used among the various turbulence models for numerical simulation (Gorobets et al., 2021b). At the same time, the results are obtained with maximum accuracy.

2. Purpose of the article

The aim of this article is to increase the thermal efficiency of aluminum ribbing convector heaters on the basis of numerical modeling, and to obtain analytical equations to determine the thermal parameters of these convectors.

Carrying out numerical simulation and obtaining computational and graphical dependencies in order to determine the thermal characteristics of convector heaters with aluminum ribbing will contribute to maintaining the correct microclimate in the room and thermal comfort of the people staying there, while ensuring energy efficiency so important in the era of construction decarbonization.

3. Examination of the convectors

The solution algorithm starts with the heat balance equation of the heating device:

$$Gc\left(t_{ent}-t_{out}\right)=k\,F\left(t_{av}-t_{in}\right) \tag{1}$$

where:

k, F – respectively: the heat transfer coefficient of the heating device [W/(m^2·K)] and the area of the heating device [m^2],

t_{av} and t_{in} – the average temperature of the heating device and of the air in the room [°C] respectively.

Equation (1) determines the heat transfer coefficient for the heating device. Criterion equations are another way to determine the heat transfer coefficient of a heating device. They determine the heat transfer coefficients from the coolant to the pipeline walls (internal α_{in}) and from the pipeline walls to the air (external α_{ext}).

The internal heat transfer coefficient α_{in} is determined by the forced movement of the heat carrier in the pipe. Initial conditions of the task: internal diameter of the pipe d [mm]; the heat carrier is water; the velocity and temperature of the coolant w_0 [m/s] and t_0 [°C] respectively; the temperature of the air in the room [°C]. Water at the temperature of t_0 has the following thermophysical properties: kinematic viscosity coefficient ν [m^2/s], thermal conductivity coefficient λ [W/(m·K)] and Prandtl criterion Pr.

The next step of the calculation algorithm: determining the hydraulic regime, i.e. the Reynolds criterion Re:

$$\mathrm{Re}=\frac{w_0\,d}{\nu} \tag{2}$$

where:
w_0 – velocity of the coolant [m/s],
d – diameter of the pipe [m],
ν – kinematic viscosity coefficient [m^2/s].

The range of $2300 < \text{Re} < 10^4$ indicates a transient flow regime in the near-wall layer. There is no criterion equation for this interval. In this regard, the article uses criterion equations for both regimes, and the results are averaged. The laminar and turbulent modes of water movement are characterized by the criterion equations for heat transfer from the coolant to the pipe wall, (3) and (4), respectively:

$$\text{Nu}_{in} = 0.17\,\text{Re}^{0.33}\,\text{Pr}^{0.43}\,\text{Gr}^{0.1}\left(\frac{\text{Pr}_m}{\text{Pr}_w}\right)^{0.25}\varepsilon_l \tag{3}$$

$$\text{Nu}_{in} = 0.021\,\text{Re}^{0.8}\,\text{Pr}^{0.43}\left(\frac{\text{Pr}_m}{\text{Pr}_w}\right)^{0.25}\varepsilon_l \tag{4}$$

where:
Gr – Grashof criterion,
Pr_m and Pr_w – the Prandtl criterion at different temperatures, at the temperature of the coolant and of the surface of the pipe, respectively;
ε_l – correction coefficient taking into account the initial distance.

The Nu_{in} criterion, defined by equations (3) and (4), is $\text{Nu}_{in} = 12.7$ and $\text{Nu}_{in} = 38.6$, respectively.

The Nusselt criterion is generally defined by equation (5):

$$\text{Nu} = \frac{\alpha\, d}{\lambda} \tag{5}$$

where:
α – heat transfer coefficient [W/(m^2·K)],
λ – thermal conductivity coefficient [W/(m·K)].

The heat transfer coefficient from water to the pipe surface α_{in} [W/(m^2·K)] is determined based on (6):

$$\alpha_{in} = \text{Nu}_{in}\frac{\lambda}{d} \tag{6}$$

Equation (3) shows that the internal heat transfer coefficient is $\alpha_{in} = 412$ W/(m^2·K), and from equation (4) – $\alpha_{in} = 1200$ W/(m^2·K). Therefore, the average value is $\alpha_{in} = 806$ W/(m^2·K).

The external coefficient α_{ext} is defined as the heat transfer during the free flow of air in an unrestricted space. The equation of the criterion of heat transfer from the pipe surface to the air:

$$\mathrm{Nu}_{ext} = 0.54\left(\mathrm{Gr}\,\mathrm{Pr}\right)^{0.25} \tag{7}$$

The Grashof criterion Gr is determined from equation (8):

$$\mathrm{Gr} = \frac{g\,d^3}{T\,\nu^2}\Delta t \tag{8}$$

where:
T – absolute temperature [K],
g – acceleration of free fall, $g = 9.81$ m/s^2,
Δt – temperature difference between air and pipe surface [°C].

Nu_{ext} criterion = 11.7. Heat transfer coefficient α_{ext} external from the pipe surface to the air:

$$\alpha_{ext} = \mathrm{Nu}_{ext}\frac{\lambda}{d} \tag{9}$$

Equation (9) shows the heat transfer coefficient α_{ext} external from the pipe surface to the air $\alpha_{ext} = 16.4$ W/(m^2·K).
Due to the high thermal conductivity of the metal, the heat transfer coefficient of the heating device is determined using the simplified formula (10):

$$k = \frac{\alpha_{in}\,\alpha_{ext}}{\alpha_{in} + \alpha_{ext}} \tag{10}$$

These results are consistent with those obtained from equation (2).

A common disadvantage of heating devices of various types is low heat transfer coefficient *k*. How to eliminate this disadvantage? Formula (10) shows that this problem is solved by increasing both heat transfer coefficients α_{in} and α_{ext}. In addition, it should be noted that it is primarily advisable to increase the smaller of the two, i.e. the external factor α_{ext}.

Experimental tests were carried out on two aluminum convectors with aluminum ribbing (Figs. 1 and 2).

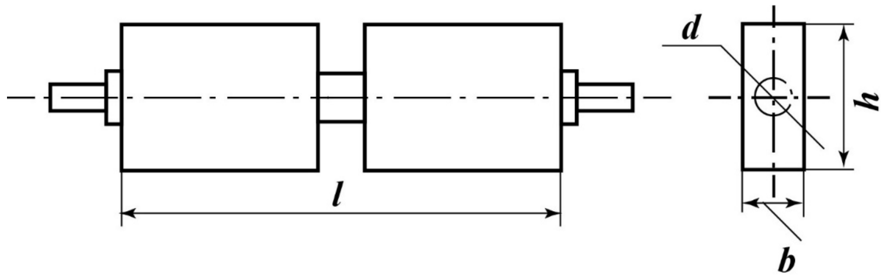


Fig. 1. The smaller convector (*own research*)

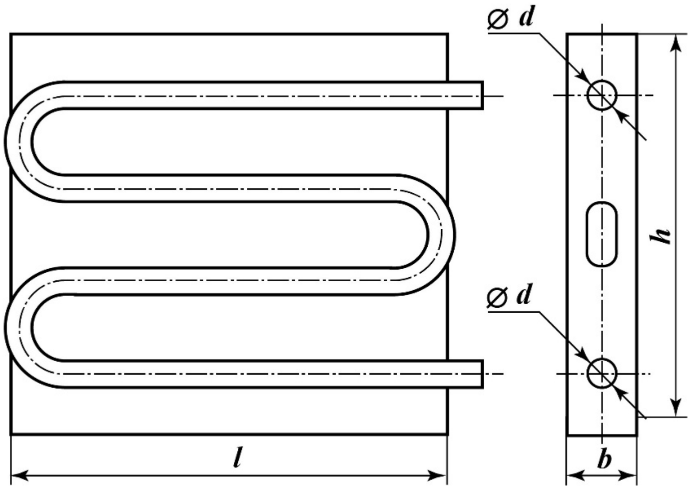


Fig. 2. The larger convector (*own research*)

Table 1 shows the experimental results of two convectors with aluminum ribbing (Figs. 1 and 2).

Table 1. Parameters of the tested convectors (*own research*)

Convectors	Area [m^2]	Weight		
		steel pipe [kg]	aluminum ribbing [kg]	general [kg]
Smaller	0.93	1.10	4.95	6.05
Greater	1.30	2.92	20.10	23.02

Based on the results of experimental measurements, the thermal power of the convectors was determined from equation (11):

$$Q = G\,c\left(t_{ent} - t_{out}\right) \tag{11}$$

where:
G – efficiency of the coolant [kg/h],
c – heat capacity of water, $c = 4.19$ kJ/(kg·K),
t_{ent} and t_{out} – temperatures of the coolant entering and leaving the convector [°C].

Coolant capacity was determined by two methods: using the weight method and rotametrically. The results were averaged. The results of the experiments showed that the smaller convector (Fig. 1) gives 194 W/m^2 of heat at normalized rates: temperature differences $\Delta t = 64.5$ °C and coolant capacity $G_1 = 35$ kg/h, and the larger one (Fig. 2) – 910 W/m^2 at $\Delta t = 64.5$ °C and $G_2 = 190$ kg/h. In addition:

$$\Delta t = 0.5\left(t_{ent} - t_{out}\right) - t_{in} \tag{12}$$

where t_{in} – air temperature in the room [°C].

Planning for a full three-factor experiment and regression analysis was conducted. A diagram was developed based on the results of the experiment (Fig. 3).

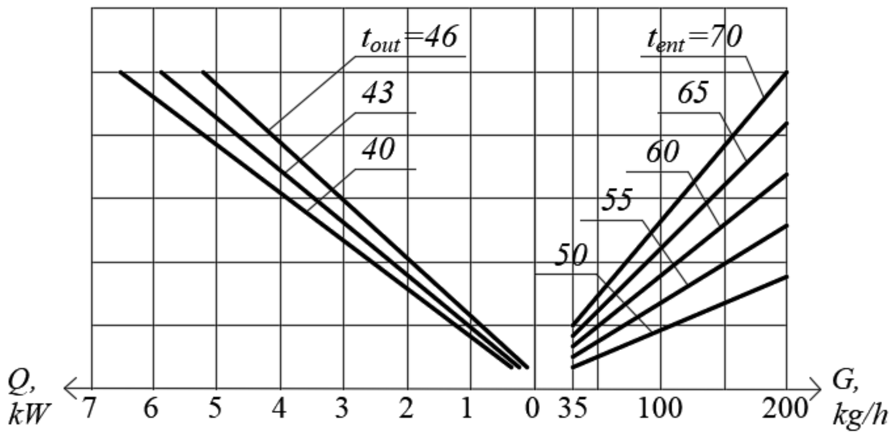
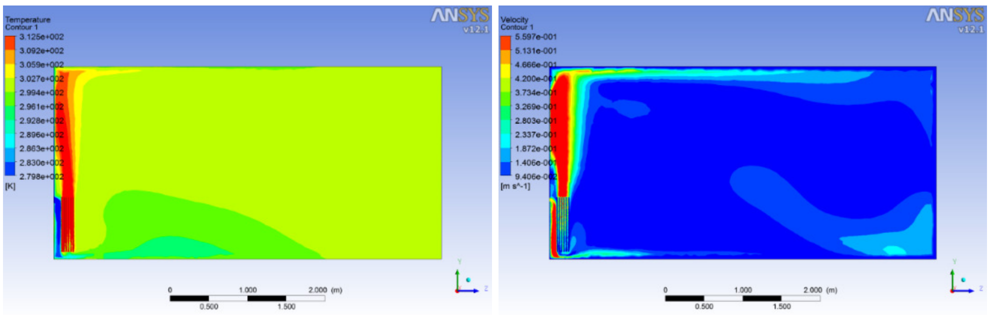


Fig. 3. Relationships of convector parameters (*own research*)

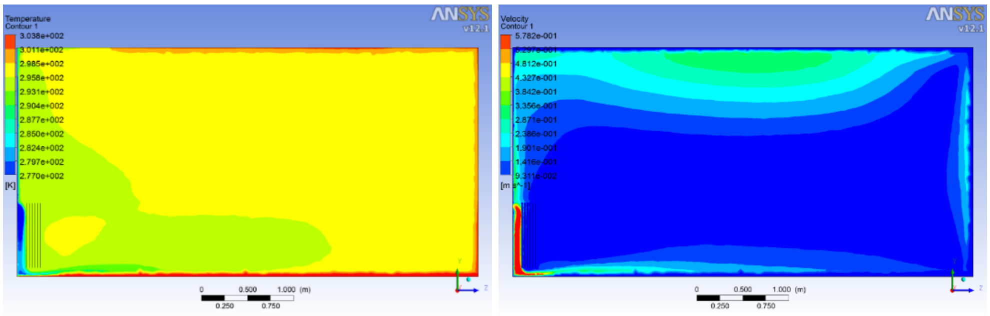
Numerical simulation was carried out using the ANSYS package. Numerical modeling determined the air temperature (Fig. 4a) and air velocity (Fig. 4b) during operation of the larger convector (Fig. 2).



a) Temperature b) Velocity

Fig. 4. Air parameters during operation of the larger convector: a) temperature; b) velocity (*own research*)

Figures 5a and 5b show the results of numerical modeling for underfloor heating: by temperature (Fig. 5a) and velocity (Fig. 5b).



a) Temperature, underfloor heating b) Velocity, underfloor heating

Fig. 5. Air parameters during floor heating: a) temperature; b) velocity (*own research*)

The results obtained using the numerical modeling method are consistent with theoretical and experimental results. Based on the data provided, it should be concluded that the studied larger convector is effective in terms of the heating area, while the smaller one requires design improvements to increase thermal efficiency, such as changing the shape of the ribbing, its thickness and the distance between ribs, as well as the production of the tubular part in the form of coils. This will enable the heating device to reduce metal consumption.

Conclusions

The conducted research allowed obtaining graphs and analytical formulas for determining convector parameters:

1. The dependence of the amount of heat on the consumption of the heat carrier, its initial and final temperature was obtained.
2. On the basis of regression analysis, it was found that the thermal efficiency of convectors depends most on the consumption of the heat carrier, and least on its temperature upon leaving the pipe.
3. A nomogram of the dependence of the amount of heat Q on the consumption of the heat carrier G and the temperature t_{in} at the inlet to the tin and outlet from the pipe t_{out} was developed.
4. It was found that the amount of heat increases with the increase in the flow rate of the heat carrier, the increase in its inlet temperature and the decrease in the outlet temperature.
5. It is expedient to make a larger convector in two versions: pass-through and ultimate.

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