Dependence of changes in the nominal heat flow of tubular heating devices on their design features

Samvel Sargsyan[1] and *Vera* Agafonova[1*]

[1] Moscow State University of Civil Engineering, 26, Yaroslavskoe shosse, 129337 Moscow, Russia

Abstract. The article is devoted to determining the nominal heat flow of a steel tubular heating device depending on the location of the pipes (vertical or horizontal), the number and diameter of pipes, as well as the value of the heat transfer coefficient. The main advantages and disadvantages of steel tubular heating devices are given. It has been determined that the mode of heat flow along the pipes in a tubular heating device changes from laminar to turbulent. As a result of the research, it was found that with a vertical arrangement of pipes in a heating device, when the coolant temperature in the pipes is 90-95°C, the height of the transition zone from laminar flow to turbulent flow varies in the range from 0.75 m to 1.25 m. If the tubular heating device is structurally made with horizontally located pipes, then the transition from the laminar flow regime to the turbulent regime is not observed. A dependence has been derived that allows one to determine the nominal heat flow of a steel tubular radiator depending on the height, number of sections, as well as the design features of the tubular heating device. A comparative analysis of changes in the nominal heat flow of a tubular heating device was carried out depending on the height, number of sections, design features, as well as the orientation of the pipes in the section. The nominal heat flux of a tubular radiator varies depending on the orientation of the pipes. It is shown that with a vertical arrangement of a tubular radiator, the value of the nominal heat flux exceeds the same value with a horizontal arrangement.

1 Introduction

Modern interior design of apartments and houses is characterized by modern and non-standard solutions for heating systems. Such solutions include tubular radiators. They quickly gained popularity both for their appearance and technical characteristics.

A modern, fundamentally new solution to heating systems - it is proposed to make the radiators more elongated. This variation is an elongated radiator, the height of which is several times greater than the width. Vertical models are not inferior in characteristics to their standard counterparts.

[*]Corresponding author: AgafonovaVV@mgsu.ru

The features of vertical tubular heating devices are as follows: complements the interior; large heat transfer area, which ensures quick heating of the entire room; vertical shape saves space; Possibility of installation in any part of the room.

The disadvantages of tubular heating devices include: complex design; uneven heating of indoor air.

The main types of vertical heating devices are as follows: tubular, consisting of several rows of steel pipes; monolithic - they represent a single solid structure that looks more massive. Both types have almost the same characteristics, and differ only in volume and recommended area for heating.

According to the type of circulating coolant, vertical tubular heating devices are distinguished: water, oil, and also using non-freezing liquids.

Centralized heating used in multi-storey buildings often requires additional calculations and mainly uses exclusively water as a coolant.

The article discusses tubular heating devices with vertical or horizontal pipes in sections made of steel. Steel is an ideal material for the manufacture of shaped tubular heating devices of a non-standard type. Steel is not inferior to cast iron in thermal conductivity, but at the same time it is a more durable material, has a smooth surface and increased strength. Water models are connected to a centralized heating system and can be used both in private and high-rise apartment buildings.

Steel radiators operate on the principle of radiant heat, which is much more efficient than convection, especially when you need to heat a spacious room with high ceilings. The surface of the device emits heat, which gradually spreads around, quickly and evenly warming the air and all objects in the room.

Each section consists of 2-6 tubes. The value of its nominal heat flow depends on how many sections the heating device includes, whether the pipes are located horizontally or vertically in a section of the heating device. The larger the room, the more sections are required for efficient heating. The general diagram of a steel tubular radiator is shown in Figure 1.

Fig. 1. General view and diagram of a vertical steel tubular heating device

Review of the status of the issue. Steel tubular heating devices have high static strength with a small wall thickness of 1.2-1.5 mm. Such heating devices are an excellent way to solve problems in central heating systems, where sudden pressure surges and water hammer are not an accident.

The shape of steel tubular radiators ensures convenient maintenance and cleaning. Dust practically does not accumulate here. For this reason, steel tubular radiators are classified as highly hygienic devices. This option is especially important for their use in medical buildings. In addition, their safety due to the absence of sharp corners also plays a big role when choosing this particular type of heating device. The reliable operation of steel tubular heating devices is ensured by their all-welded design, created using spot welding with the absence of gaskets between sections.

The height of steel tubular radiators can reach up to three meters and above. The length and depth of the appliances are entirely dependent on the heat flow needs in accordance with the heating system capacity for the heated room.

Methods of connecting steel tubular heating devices to the heating system can be: bottom; lateral; diagonal.

To improve technical performance and increase service life, steel tubular heating devices are coated from the inside with special polymer compounds.

A steel tubular heating device, a device that consists of several sections. Inside each of them there are special channels through which the coolant moves. Steel tubular heating devices transfer heat to the heated room by convection and radiation. The paint color of the heating device, as a secondary factor, also affects the value of the rated heat flux of the heating device.

The nominal heat flow from steel tubular heating devices depends on the length, diameter and number of vertically or horizontally located pipes in sections. When calculating the nominal heat flow of a steel tubular heating device, it is necessary to take into account that heat transfer depends on the length of the pipes in the sections, their number and orientation of location. The heat flow from a tubular heating device depends on the orientation of the pipes in the sections. When the pipes are arranged vertically in the heating device, a reserve of additional power is created, aimed at increasing the value of the rated heat flow from steel tubular radiators. The size of the reserve of the nominal heat flow from a heating device can be estimated using the features of free-convective heat exchange along steel pipes in the sections of the heating device in question.

2 Materials and methods

2.1.Formulation of the problem

The purpose of this article is to determine the nominal heat flow of a vertical steel tubular heating device, taking into account the increasing value of the heat transfer coefficient along the height of the pipe, its diameter and quantity in the section under consideration.

Some of the pipes in the sections of a vertical tubular heating device are located horizontally, and some are vertical, and the heat transfer from them is different. It must be taken into account that the calculation of heat transfer from pipes in the section of the heating device (or cylinders) in question has been well studied for pipes that are located at a sufficient distance from the walls. At the same time, there is little data on the heat transfer of vertically or horizontally located pipes in a heating device located in close proximity to the enclosing structures. The article examines heat transfer from horizontal and vertical pipes as part of a steel tubular heating device, neglecting the influence of walls located in close proximity to it [1-18].

2.2. Calculation methods

The heat transfer coefficient, according to the theory of similarity, is determined by the value of the Nusselt criterion. The criterion equation in general has the following form:

$$\mathrm{Nu} = \mathrm{C} \cdot (\mathrm{Gr} \cdot \mathrm{Pr})^{\mathrm{n}} \cdot \mathrm{K} \quad (1)$$

$$\mathrm{Nu} = \alpha \cdot \frac{\mathrm{X}}{\lambda}$$

where: α - heat transfer coefficient from the outer surface of the pipes into the heated room, W/(m^2 °C); X - characteristic size of the transition of the air movement mode in a convective jet, m; λ - thermal conductivity of air, W.

The Grashof number is defined as:

$$\mathrm{Gr} = \frac{\mathrm{g} \cdot \beta \cdot \rho^2 \Delta \mathrm{T} \cdot \mathrm{X}^3}{\mu^2} \quad (2)$$

where: β - temperature coefficient of volumetric expansion of air, 1/°C; ΔT - temperature difference between the pipe wall and the ambient air in a heated room, °C; ρ - air density, kg/m^3; μ - dynamic viscosity of air in a heated room, N·s/m^2 , g = 9,81 m/s^2

The Prandtl number is defined as:

$$\mathrm{Pr} = \frac{\mu \cdot \mathrm{c_p}}{\lambda} \quad (3)$$

where: c_p - heat capacity of air, J/(kg °C); λ - thermal conductivity of air, W; μ – dynamic viscosity of air, N·s/m^2.

The mode of flow around the wall of pipes as part of a section of a steel tubular heating device is determined by the value of the Rayleigh number (criterion), defined as:

$$\mathrm{Ra} = \mathrm{Gr} \cdot \mathrm{Pr} \quad (4)$$

In this case, the flow regime is laminar when the Rayleigh number varies in the range 10^4<Ra< 10^9. In cases where the Rayleigh number is greater than 10^9 (Ra>10^9), the mode of movement of convective flows is turbulent. It should be noted that when the Rayleigh number is less than 10^3 (Ra<10^3), then free-convective heat exchange along the surface of the steel pipes of the heating device in question can be neglected [19-20]. For horizontally located pipes of the heating device in question, due to the insignificant value of the characteristic size X=d_{out}, где d_{out} - pipe outer diameter, laminar flow mode. Heat exchange of vertically located pipes in a steel tubular heating device must be carried out in two zones [21]. In the lower zone of a vertically located pipe, the convective flow is laminar, and in the upper zone of a vertically located pipe in the heating device under consideration, the movement mode is turbulent.

Based on the above, the zone boundary (L_{cr}) must be found using the formula:

$$\frac{\mathrm{g} \cdot \beta \cdot \rho^2 \cdot \Delta \mathrm{T} \cdot \mathrm{L_{cr}^3}}{\mu^2} \cdot \frac{\mu \cdot \mathrm{c_p}}{\lambda} = 10^9 \quad (5)$$

Table 1 presents the coefficients for calculating the value of the Rayleigh criterion depending on the location of the pipes in the section in the steel tubular heating device under consideration and the mode of movement of the heat flow along the pipes [22].

Table 1. Coefficients for calculating the value of the Rayleigh criterion

№ p.p.	Pipe location	Wrap mode	C	n	K
1	Horizontally	Laminar	0,47	1/4	1
2	Horizontally	Turbulent	0,1	1/3	1
3	Vertical	Laminar	0,686	1/4	$(Pr/(1+1,05 \cdot Pr))^{1/4}$
4	Vertical	Turbulent	0,15	1/3	1

Table 2 presents the values of the heat transfer coefficient from the outer surface of the pipe into the air volume of the heated room, depending on the mode of flow around it, W/(m^2 °C).

To determine the heat transfer of pipes in a section of a steel tubular heating device, it is assumed that for both horizontal and vertical pipes the flow regime is laminar [23]. For a horizontal pipe, the above is valid. For a vertically located pipe, this requirement is not always met. Calculations to determine the boundaries of the transition zones from the laminar flow regime to the turbulent flow regime showed that the height of the transition zone from the laminar flow to the turbulent regime varies within 0,75…1,25 m depending on the temperature of the coolant in a vertically located pipe in the tubular heating section device. The vertical part of a steel tubular heating device in a heated room can be significant. The height of the heating device in question was taken to be 1750 mm.

Table 2. Values of the heat transfer coefficient from the outer surface of the pipe into the air volume of the heated room, depending on the mode of flow around it, W / (m^2 °C)

T_1-$T_в$	Radiative heat transfer coefficient, α			Radiative heat transfer coefficient, $α_r$	Total heat transfer coefficient under different flow regimes for a vertical pipe	
	Laminar mode		Turbulent mode		Laminar mode	Turbulent mode
	Horizontal pipe	Vertical pipe				
10	2,59	3	3,87	5,7	8,7	9,57
20	3,24	3,57	4,86	6,0	9,57	14,43
30	3,69	3,95	5,53	6,31	10,26	15,79
40	4,04	4,24	6,07	6,63	10,87	16,94
50	4,34	4,48	6,5	6,97	11,45	17,95
60	4,59	4,69	6,88	7,32	12,02	18,9
70	4,81	4,87	7,21	7,69	12,56	19,77

The assessment of the radiative component of heat exchange between a pipe in a section of a vertical tubular steel heating device and the ambient air of a heated room is carried out using the Stefan-Boltzmann radiant heat exchange formula.

$$Q_r = \varepsilon \cdot \sigma \cdot ((T_1 + 273)^4 - (T_{in} + 273)^4), \qquad W/m^2 \qquad (6)$$

where: ε - emissivity, σ - Stefan-Boltzmann constant.

Reducing equation (6) to the form of the heat transfer equation, we obtain:

$$Q_r = \alpha_r \cdot (T_1 - T_{in}) = \frac{\varepsilon \cdot \sigma \cdot ((T_1 + 273)^4 - (T_{in} + 273)^4}{(T_1 - T_{in})) \cdot (T_1 - T_{in})} \quad (7)$$

where: α_r – radiant heat transfer coefficient.

Table 2 shows the calculated values of the radiant heat transfer coefficient and the total heat transfer coefficients.

Heat release from the pipes of vertical steel tubular heating devices into the room must be taken into account taking into account the coefficient η, which takes into account the location of the pipes. The upper location of the pipeline leads to heating of the upper zone due to the release of free-convective heat from the vertically located pipes, which leads to overheating of the internal surfaces of the enclosing structures of the ceiling and the upper zone of the walls. The serviced area is heated due to radiant heat exchange and return jets of ascending convective flows.

3 Discussion of results

Based on the obtained dependencies, calculations were made to determine the nominal heat flow of a steel tubular heating device depending on the number of pipes in the section, the length (height) of the pipes and the diameter. It has been determined that the critical height for the transition of the convective flow regime along a vertically located pipe from laminar to turbulent regime is 0.75 m. Figure 2 shows the dependence of the nominal heat flow of a tubular heating device on the design of the location (vertical), height, diameter and number of pipes in the section. For steel tubular vertical heating devices, the heat flow increases with the transition of the mode of movement of the convective flow along the pipes of the heating device after the critical height.

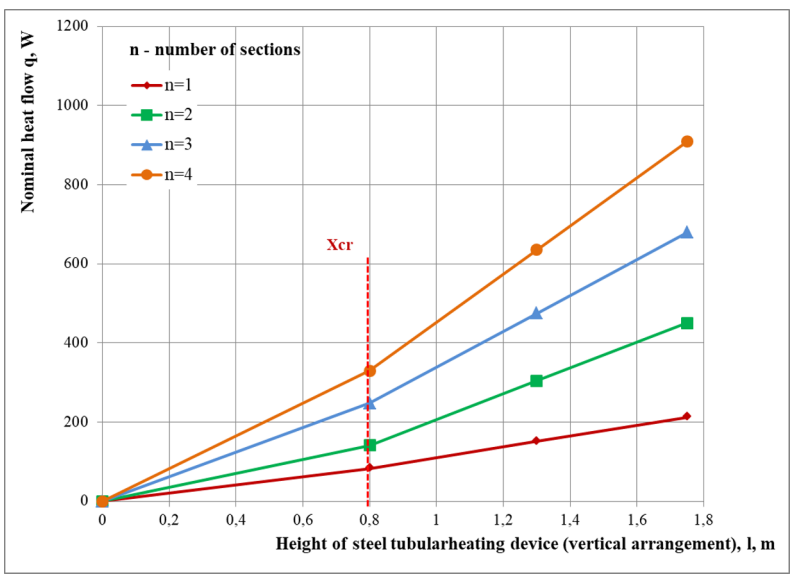

Fig.2. Dependence of the nominal heat flow of a tubular heating device on the design of the location (vertical), height, diameter and number of pipes in the section

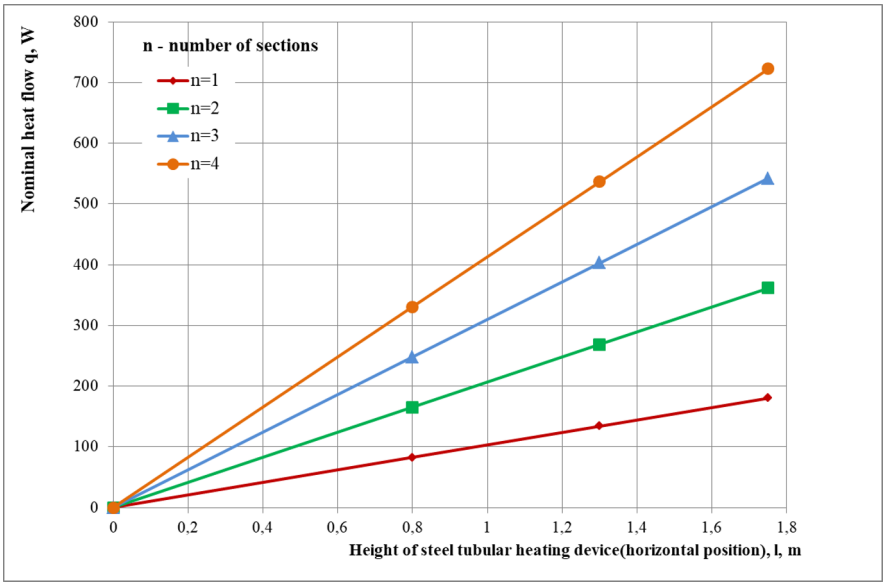

Fig. 3. Dependence of the nominal heat flow of a tubular heating device on the design of the location (horizontal), length, diameter and number of pipes in the section

Figure 3 shows the dependence of the nominal heat flow of a tubular heating device on the design of the location (horizontal), length, diameter and number of pipes in the section. For steel tubular horizontal heating devices, the mode of movement of convective flows along the entire length of the pipe remains laminar, and the magnitude of the heat flow increases according to the characteristic of the straight line equation.

4 Conclusions

As a result of the study, the following results were obtained:

1. The height of the transition zone from laminar flow to turbulent mode varies within 0.75...1.25 m depending on the temperature of the coolant in the vertical pipe in the section of the heating device.
2. A dependence has been derived that allows one to determine the nominal heat flow of a steel tubular heating device depending on the height and number of pipes and sections.
3. It is concluded that the nominal heat flow in the zone of laminar air movement does not change, and when the mode transitions to turbulent, the value of the heat flow along the height of the heating device increases sharply.
4. The design of the arrangement of pipes (horizontal or vertical) as part of a section of a tubular heating device is a secondary factor affecting the value of the nominal heat flux density.
5. At low values of average temperature difference (35°C), the arrangement of pipes in the design of a tubular heating device in water heating systems does not affect the heat flow density.

References

1. B.M. Ashe, Heating and ventilation: Part 1. Heating (Moscow, Gosstroyizdat, 1939)
2. V.L. Granovsky, ABOK **4** (2014)

3. V.L. Granovsky , Energy saving **6**, 38-48 (2021)
4. S.V. Sargsyan, E.V. Voitovich, V.Yu. Kravchuk, Industrial and civil construction **6**, 58-62 (2022)
5. V.I. Sasin, Aqua-Therm **6** (94), 24-27 (2016)
6. V.I. Sasin, G.A. Bershidsky, T.N. Prokopenko, B.V. Shvetsov, ABOK **4**, 46-48 (2007)
7. V.I. Sasin, G.A. Bershidsky, T.N. Prokopenko, V.D. Kushnir, Akva-Therm **5**, 71-73 (2013)
8. S.V. Sargsyan, Scientific review **16**, 68-71 (2015)
9. S.V. Sargsyan, Scientific review **16**, 76-79 (2015)
10. V.I. Sasin ABOK **1**, 58-62 (2019)
11. V.I. Sasin ABOK **1**, 30-34 (2017)
12. Modern heating systems for residential buildings: opinions of international experts, ABOK **5**, 4-14 (2019)
13. ABOK Standard 4.2.2-2006, Heating radiators and convectors. General technical conditions (Moscow, AVOK-PRESS, 2006)
14. G.A. Bershidsky, M.Ya. Poz, ABOK: Ventilation, heating, air conditioning, heat supply and building thermophysics **3**, 64-80 (2017)
15. D.A. Plotnikov, S.I. Stytsenko, Plumbing, Heating, Air conditioning **8** (236), 18-22 (2021)
16. A. Moftakhari, C. Aghanajafi, A. Ghazvin, Inverse Problems in Science and Engineering. **25**(4), 1-28 (2016)
17. G. Sevilgen, M. Kilic, Energy Build **43**,137-146 (2011)
18. A. Jahanbin, E. Zanchini, Applied Thermal Engineering **105**, 467-473 (2016)
19. A. N. Skanavi, L. M. Makhov, Heating (Moscow, ASV, 2008)
20. O.G. Martynenko, Yu.A. Sokovishin, Free-convective heat transfer: Handbook (Minsk, Science and Technology, 1982)
21. H. Wang, Basic formulas and data on heat transfer for engineers: Handbook (Moscow, Atomizdat, 1979)
22. Heat and mass transfer. Thermotechnical experiment: Handbook (Moscow, Energoizdat, 1982)
23. Internal sanitary systems: Part 1. Heating (Moscow, Stroyizdat, 1975)