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Mathematical modeling of complex heat transfer in a closed internal volume of a high-temperature radiant heater

Andriy Redko[1] (*orcid id: 0000-0003-2331-7273*)
Oleksandr Redko[1] (*orcid id: 0000-0002-9375-1262*)
Natalia Kulikova[1] (*orcid id: 0000-0001-8226-7961*)
Yurii Burda[1] (*orcid id: 0000-0003-3470-1334*)
[1] Kharkiv National University of Construction and Architecture

Abstract: The results of a numerical analysis of the parameters of a radiant heating system with radiating panels are presented. The effect of the shape and dimensions of the panel, surface material and the presence of thermal insulation are numerically investigated. It is found that the device of re-radiating panels reduces the surface temperature to 450-500°C, but the increase in the surface area of the radiator provides a more uniform radiation intensity over the heated area, not exceeding the permissible parameters according to sanitary and hygienic requirements. The panel device is found to transform the parameters of the short-wavelength radiator into a more comfortable long-wavelength radiator mode.

Keywords: radiant heating, radiating panels, heating system, infrared burner

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Introduction

Gas burners of infrared radiation are widely used in the heating systems of industrial enterprises. High-temperature radiators with a surface temperature of 600 to 1200°C provide heating to premises of large volumes and heights in which other heating systems are ineffective. Heating systems with infrared burners are used for all types of buildings (machine-building, transport, agricultural enterprises, shopping centers, exhibitions, gyms, etc).

However, high-temperature light radiators have limitations, namely the high radiation power and the acute angle of the radiation flux create a significant unevenness in the room in terms of area and height of the room.

Moreover, the implementation of sanitary standards is difficult to ensure due to the long and intense short-wave radiation, which has an adverse effect on body tissues and retina and is accompanied by a deterioration in general state (Yazovtsev et al., 2011).

The results of the experimental study (Kurilenko, 2015) show that the distribution of the heat flux density from the 20 kW radiator is q = 201 W/m^2 (h = 0.5 m) and q = 167.5 W/m^2 (h = 1.0 m). The air temperature under the light radiator with a power of 30 kW is (305-345°C) at a distance of 200 mm and (152-172°C) at a distance of 1000 mm (Kurilenko, 2015).

Due to the low efficiency of high-temperature radiators, being less than 20%, attempts are being made to increase this value (Slesarev, 2009; Slesarev et al., 2009). Heat losses are convective losses with effluent gases and of the burner body. Also, heat is lost during free convection when air flows around the open surface of the radiator and the grid. To reduce convective heat losses, burners are equipped with a transparent screen with openings for the removal of combustive products. The screen transmits about 80-87% of the radiation, part being absorbed by the screen and part being reflected on the ceramic radiator, which increases the efficiency of the burner. The area of the screen is equal to the radiator area. In this case, the radiation length increases and the intensity decreases, but due to the small area of the radiator and the acute angle, the unevenness of the radiation intensity remains the same.

A change in air temperature near the surface of the radiator (Kuznetsov et al., 2013) shows that there is a change in air temperature from 335°C (x = 0.1 m) to 110°C (x = 1.5 m). A diagram of a modernized reflector according to the "water shirt" principle which reduces heat loss towards the building ceiling and avoids moisture condensation on the inner surface of the roof is given in the article (Kurilenko et al., 2012). However, the complexity of the design does not significantly increase the efficiency of the infrared heating system (about 10%). The short radiation wavelength and high radiation intensity create problems in ensuring comfortable conditions in the working area.

The results of the study into the parameters of infrared radiation gas systems are presented in (Avdeeva et al., 2010; Kurilenko, 2015; Kurilenko et al., 2012; Kuznetsov et al., 2013; Pelipenko & Slesarev 2012; Shivanov 2007; Slesarev, 2009; Slesarev et al., 2009; Solnyshkova 2012). Moreover, the test results indicate a lack of efficiency.

The aim of this work is to study the radiant heat exchange in a closed volume of a panel-radiator system and to change the temperature of the lower radiator surface.

1. Object and research methods

The mathematical model of a three-dimensional unsteady flow and complex heat exchange in a radiant heating system is based on the system of Reynolds--averaged Navier-Stokes equations, supplemented by the radiative transfer equation. To construct a discrete analogue of the system of differential equations, the finite-volume method was used (Redko et al., 2019).

To make a comparative assessment of the various designs of the panel radiator, a numerical simulation of the complex heat exchange was performed. In the numerical simulation, the following assumptions were made: the geometry of the panel radiator is mirror-symmetric and the environment inside the panel radiator is translucent. The process of heat conduction inside the wall material is one-dimensional. Heat transfer from the panel radiator to the environment of the room is carried out exclusively by radiation. The walls of the panel radiator are completely black.

The re-radiating panel is suspended from the bottom to the radiating surface of a standard IR-radiator, forming a closed cavity with three walls: upper, lower and closing. The length of the panel radiator is much greater than its height and width. The walls of the panel radiator re-emit heat to each other. The air inside the panel radiator is heated as a result of heat conduction and natural convection. The working surface of the box is the bottom wall that re-radiates heat to the working area of the room. The following assumption is made: the combustion products are removed upward into the slotted channels close to the radiator and their movement does not affect the parameters in the panel radiator. The heat re-emitted into the environment by the closing wall is defined as losses. The design of the re-emitting panel should provide minimal heat loss by convection, maximum uniformity of the temperature distribution of the lower wall and minimum material consumption.

Diagrams of the computational regions of the panel radiator and computational grids are shown in Figures 1 and 2. The computational regions were covered by uneven structured grids formed by a single layer of hexahedral cells. The number of calculation cells in options No. 1, 1a, 4-7, 7a, 7b was 1575, in option No. 2 - 3225, in option No. 3 - 4725. Angular discretization of the calculation area was performed in 20 directions with pixelization of 3 pixels per control angle. A stationary solution was found by the time-based determination method. The time integration step was 0.1 s.

2. Results and discussion

The design of the computational experiment is given in (Table 1).

Table 1. Plan of the computational experiment (*own research*)

Parameter	A [m]	B [m]	C [m]	D [m]	$\delta_{c.w}$ [m]	$\delta_{o.w}$ [m]	$\lambda_{o.w}$ [W/m·°C]	$\lambda_{c.w}$ [W/m·°C]	λ_{in} [W/m·°C]
Variant No. 1	0.15	0.25	0.45		0	0	0	∞	0
Variant No. 1a	0.15	0.25	0.45		0	0	∞	∞	∞
Variant No. 2	0.15	0.5	0.45		0	0	0	∞	0
Variant No. 3	0.15	0.5	0.45	0.1	0	0	0	∞	0
Variant No. 4	0.15	0.5	0.45		0	0	0	∞	0
Variant No. 5	0.15	1	0.45		0	0	0	∞	0

A, B, C, D - geometric dimensions, δ_w - duct wall material, λ_w - thermal insulation conditions of the closing walls

The shape of the panel radiator, its dimensions, wall material and thermal insulation conditions varied. In all calculations, the temperature of the upper wall was taken to be equal to 900°C, and the radiation temperature of the environment was +10°C. The calculation results are presented in Figures 3-5 and in Table 2.

Table 2. The flux density of the incident radiation and the temperature of the lower wall of the panel emitter (*own research*)

Parameter	$E_{d.min}$ [W/m^2]	$E_{d.max}$ [W/m^2]	$E_{d.av}$ [W/m^2]	$(E_{d.max} - E_{d.min})/$ $/E_{d.av} \cdot 100$ [%]	T_{min} [°C]	T_{max} [°C]	T_{av} [°C]	$T_{max} - t_{min}/$ $/t_{av} \cdot 100$ %
Variant No. 1	73636	197790	144123	86	395	630	539	44
Variant No. 1a	43061	167673	107625	116	279	604	471	69
Variant No. 2	108333	199702	147569	62	470	633	544	30
Variant No. 3	109359	199682	147794	61	472	633	545	30
Variant No. 4	104874	158478	142217	38	474	577	547	19
Variant No. 5	114934	134867	128617	15	498	539	528	8
Variant No. 6	48692	116494	83492	81	329	522	436	44
Variant No. 7	61751	95040	81921	41	384	477	442	21
Variant No. 7a	61788	95203	82027	41	385	478	442	21
Variant No. 7b	49036	83919	70167	50	351	461	419	26
Variant No. 8	63864	87975	74564	32	395	463	426	16

A trapezoidal re-emitting panel radiator with a width of 1800 mm and a height of 1000 mm, made of 1 mm thick sheet steel with a heat-insulated closing wall (option No. 7a) can be proposed as optimal.

Figure 3 show the value of the radiation density and the wall temperature of the panel radiator of various shapes. The trapezoidal panel radiator is seen to have a bottom surface temperature of about 600°C and a radiation density of 180,000-190,000 W/m^2.

The calculations were performed for the „radiator-panel" systems of various geometric configurations. Part of the radiating panel, located at an angle to the radiator, has a lower temperature than in the center, reaching 530-470°C. The temperature in the center of the radiating panel reached 600-700°C. The sides of the panel also have a high temperature that increases heat loss. More favorable conditions are in the trapezoidal system since the panel sides re-radiate thermal energy to the lower plane.

The airflow lines and velocity values in the „radiator-panel" system show that the most intense air circulation in the system is also observed in a trapezoidal system. Air velocity values vary from 1 to 2 m/s. In rectangular systems, stagnant zones in the air motion are observed.

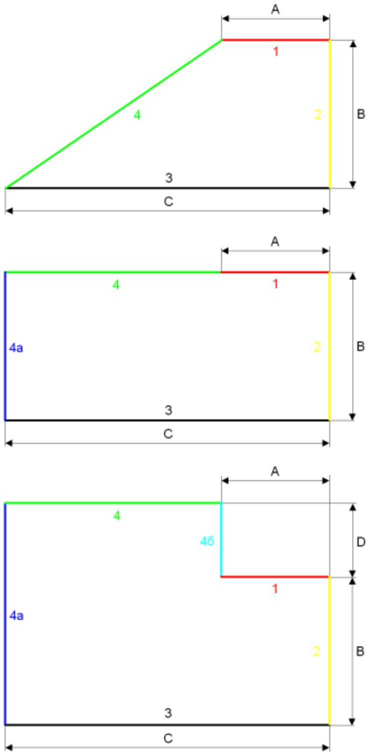

Fig. 1. Schemes of computational domains: from top to bottom - options No. 1 (1a, 4-7, 7a, 7b); No. 2; Number 3; 1 - emitter; 2 - plane of symmetry; 3 - bottom wall; 4, 4a, 4b - closing walls (*own research*)

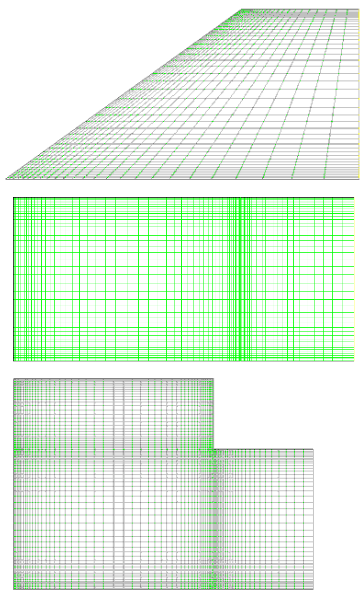

Fig. 2. Settlement grids: from top to bottom - options No. 1; No. 2; No. 3 (*own research*)

In the option No. 1 ($\lambda_{c.w}$= 0), i.e. when there is thermal insulation on the side wall, the air temperature in the system is higher (600-180°C) than in the case of $\lambda_{c.w} = \infty$ (option No. 1a). This shows the effect of the distance between the radiator and the lower screen (from 0.25 to 1.0 m) with a half panel length value of 0.45 m. The distance value is increased from 0.5 to 2.0 m at a half-panel length of 0.9 m (see Fig. 4). As you can see, the air temperature in the system (options No. 1, 4, 5) is higher, and the panel temperature is 520-550°C and in options No. 6, 7, 8 (550-600°C), respectively. The incident radiation density on closing side walls in options No. 1, 4 and 5 is also higher and amounts to 75 000-125 000 W/m^2. Figure 5 shows the temperature values of a screen made of 1 mm thick steel (λ = 16.27 W/m·K) with thermal insulation of the side wall. The temperature of the panel is 400-450°C. In addition, Figure 5 shows the temperature values of the system walls; in this case the radiator panel is made of 1 mm thick aluminum (λ = 202.4 W/m·K) and the side wall is also thermally insulated. The temperature of a steel screen is 475°C (an aluminum screen is about 450°C). Heat transfer is observed by means of thermal conductivity along the screen resulting in a decrease in the screen temperature.

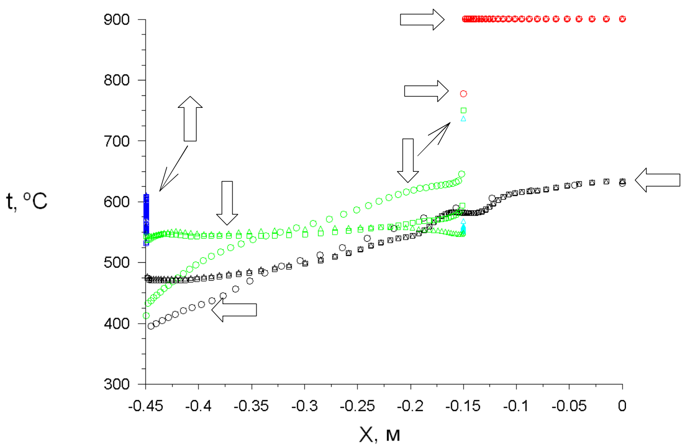

Fig. 3. Temperature (°C) of the walls of the boxes of various shapes ($\lambda_{z.w}$ = 0; $\lambda_{n.w} = \infty$): ○ - option No. 1; □ - option number 2; Δ - option number 3; ⇒ - emitter; ⇐ - bottom wall; ⇓ - closing wall; ⇑ - vertical sections of the trailing wall of option No. 3 (*own research*)

Table 2 shows the values of the radiation density of the system walls. The values of the radiant flux density on the lateral surface indicate possible heat losses in the system. It is shown that the distribution of the incident radiation flux density is affected by geometric parameters, system configuration (dimensions of the radiator and screens, distance between the radiator and the screen), screen material and the presence of thermal insulation on the sidewall, as well as other factors. The density of the incident radiation flux is shown to have maximum values along the axis of the radiator and the heat flux density is shown to decrease at an angle (with its increase).

The results of the numerical study show that the use of panel radiators can improve the uniformity of the radiation density by increasing the angle of the radiation flux and the shape of the lower panel with the profile of the radiating lower panel being convex, multi-stage or multi-edge.

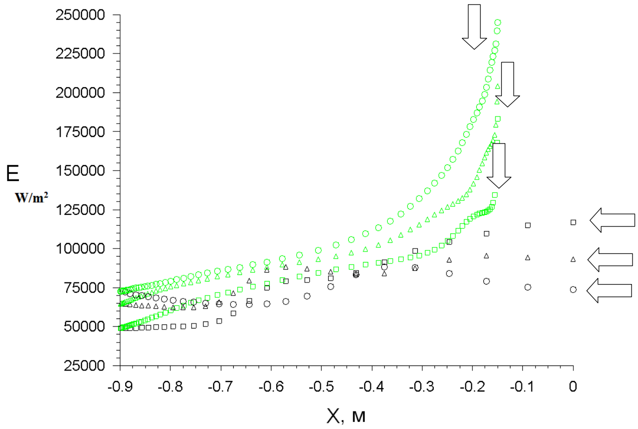

Fig. 4. The flux density of incident radiation [W/m^2] on the walls of panel emitters of different heights at C = 0.9 m ($\lambda_{z.st} = 0$; $\lambda_{n.st} = \infty$): □ - option No. 6 (B = 0.5 m); Δ - option No. 7 (B = 1.0 m); ○ - option No. 8 (B = 2.0 m); ⇐ - bottom wall; ⇓ - closing wall (*own research*)

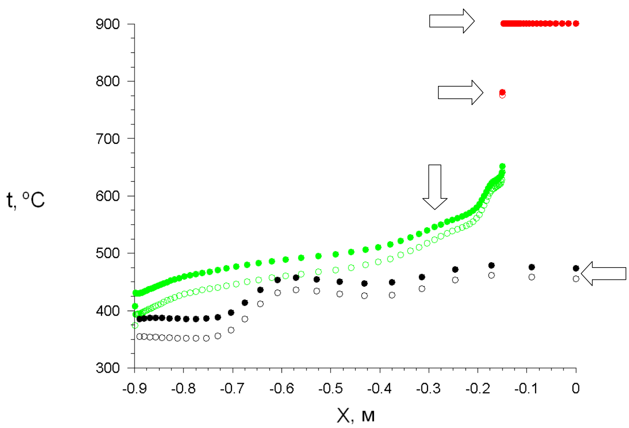

Fig. 5. Temperature [°C] of the walls of panel emitters made of various materials (C = 0.9 m): ● - option No. 7a ($\lambda_{c.w} = \lambda_w = 16.27$ W/(m·°C) (steel), $\delta_{c.w} = \delta_{o.w} = 1$ mm, the trailing wall is thermally insulated ($\lambda_{iz} = 0$)); ○ - option No. 7b ($\lambda_{c.w} = \lambda_{o.w} = 202.4$ W/(m·°C) (aluminum), $\delta_{c.w} = \delta_{o.w} = 1$ mm, the closing wall is thermally insulated ($\lambda_{iz} = 0$)); ⇒ - emitter; ⇐ - bottom wall; ⇓ - closing wall (*own research*)

Conclusion

As a result of the numerical study, it is found that the effect of the geometric parameters of the radiator and panel is observed; it is also found that trapezoidal radiators made of 1 mm thick sheet steel with a heat-insulated wall are more efficient; the surface temperature of the radiator panel changes from 426 to 547°C (options No. 8 and No. 4, respectively) with a decrease in the distance of the panel to the radiator surface from 2.0 m to 0.5 m and with a decrease in panel width from 0.9 m to 0.45 m, respectively; the effect of the heat conductivity coefficient (steel - λ_{st} = 16.27 W/m·K; aluminum - λ_{al} = 202 W/m·K) of the radiating panel material is found as well while the temperature of the radiating aluminum surface is 350-425°C, and of steel screen is 400-450°C; moreover, the radiation unevenness of filler structures is reduced depending on the height the radiators and the step of their location, being 10-20%. In addition, it is found that the values of radiation density by high-temperature short-wave radiators with panels are close to the radiation density of long-wave radiators.

The results of the numerical study obtained in this work indicate the possibility of creating a more uniform radiation intensity density when placing additional screens around a high-temperature radiator.

In order to reduce the unevenness of heating the area, a modification of the radiator design was made.

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Określanie parametrów promieniowego systemu grzewczego z panelami promieniowymi

Streszczenie: Przedstawiono wyniki numerycznej analizy parametrów promiennikowego systemu grzewczego z panelami promieniującymi. Numerycznie zbadano wpływ kształtu i wymiarów panelu, materiału powierzchni oraz obecności izolacji termicznej. Ustalono, że urządzenie obniża temperaturę powierzchni do 450-500°C, ale wzrost pola powierzchni emitera zapewnia bardziej równomierne natężenie promieniowania w ogrzewanym obszarze, nie przekraczając dopuszczalnych wymagań sanitarnych i higienicznych. Stwierdzono, że urządzenie panelowe przekształca parametry promiennika o krótkiej długości fali w bardziej komfortowy tryb promiennika o dużej długości fali.

Słowa kluczowe: ogrzewanie promiennikowe, panele promieniujące, system grzewczy, palnik na podczerwień