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Specificity of Temperature Mode Formation in Production Premises with Infrared Heating System

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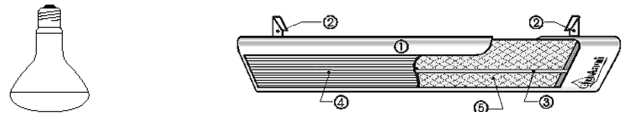
Abstract: This paper deals with a detailed analysis of the results of experimental investigations into the temperature regime of a production premises in which infrared heaters are used. Described is the process of temperature regime formation, and determined are the factors that influence it. The data obtained here has been processed using the well-known methods of mathematical statistics. These methods determine how the temperature regime formation in a production area is affected by factors such as irradiation intensity, degree of irradiation surface blackness, and air velocity over the irradiated area. Obtained are the diagrams and empirical dependences of the air temperature above the irradiated area. The results of these experimental investigations have shown that an increase in the air velocity over the irradiated area causes the air temperature to drop. The investigation results can be applied in the engineering design of heat supply systems for production premises, using infrared heaters, and in designing the radiant heating systems in buildings and facilities used for industrial and agricultural purposes.

Index Terms—**irradiation intensity, irradiated area, infrared heater, production premise.**

I. INTRODUCTION

One of the most critical concerns of EU and USA energy policy is saving energy sources in technological processes in various industrial and agricultural sectors [5], [16]. The main requirement of heating systems in industrial premises is to maintain the microclimate parameters within the production areas [1], [14], [2]. Compared to air or convective heating systems which are quite energy-consuming, more efficient systems could be used to localize the heating and to ensure a dynamic heating regime [12]. For this reason infrared heating systems are increasingly being used in the EU and USA. According to the investigation data [10], [3]; [9], the use of infrared emitters could save up to 40 – 50% of energy resources when compared to other heating systems. A proper layout of infrared emitters allows for the heating of the premise's production area. Due to this, there is no need of heat loss compensation in the entire premise space, thus allowing for decreasing the consumption of fuel and energy resources. A wide use of infrared heaters results in reducing the atmospheric pollution by combustion products coming from heat-generators. This is the positive ecological aspect of using the infrared heating systems. The temperature on the surface of infrared heating devices can vary within wide limits. The temperature in electric radiant emitters is in the range of 400 – 2000ºC [11], while in gas-fired radiant emitters it varies from 850 to 950 ºC [13]. 70 – 80% of the radiant heater's nominal heating efficiency is ensured by direct radiation, while the remaining part is ensured by radiation and convection, as well as by direct convection [16]. The heaters exist as electric incandescent lamps and radiant panel lamps (Fig. 1). In designing the infrared heaters using modern eco-friendly heat-insulating materials, these devices can be used in existing buildings with timber floors or wooden interior elements.



(a) (b)

Fig.1. Infrared heaters:
(a) Incandescent reflector lamps; (b) infrared panel heater
1 – Metal frame; 2 – fastener; 3 – quartz-sheathed low temperature heating coil; 4 – aluminum shape; 5 – shield

Due to the variety of infrared heating system constructions and their operating principles, an appropriate regulation of the temperature in the premise's production area is ensured. The infrared heating systems are used to maintain the required temperature in this area taking into account the changes in temperature parameters during the entire heating period. The term "production area of the premise" means the space above the floor level where the permanent workplaces are located to perform necessary production processes. An irradiated area is the surface area exposed to thermal radiation produced by the infrared heater (Fig. 2).

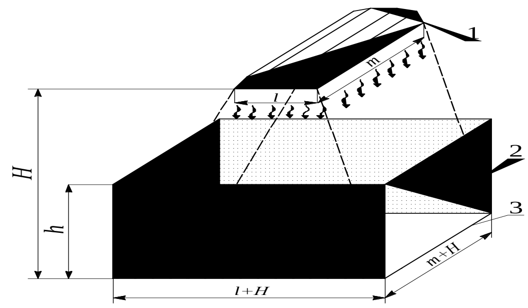


Fig.2. Designation of the production premise's areas:
1 – Infrared heater; 2 – premise's production area; 3 – irradiated area

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H – mounting height of the infrared heater; *h* – height of the premise's production area;
l – heater width; *m* – heater length; l+*H* – width of the irradiated area; *m*+*H* – length of the irradiated area

When using infrared heaters in production premises, there is a need to conduct extensive parametrical investigations into the temperature regime of the production area. This allows us to determine the dependences of the irradiated area temperature regime as well as the potential factors that influence this regime. In large premises the temperature regime in the production area is influenced not only by the temperatures of the heated surfaces and their degree of blackness, but also by the air temperature above the irradiated area, air velocity, background air temperature, and irradiation intensity. The infrared heaters which are used in production premises ensure a localized heating of the production area. The floor surface heating results in the lifting of warm air being displaced by cold air. Air mass movement over the irradiated area is caused by the difference between the air density above the heated floor surface and the air density in the premise [4], [7]. The vertical convective flow is characterized by the air temperature above the irradiated area t_{air}, ºC and may be conditionally divided into the following sections: ABCD – boost zone; BEFC – transition zone; EGHF – base section (Fig. 3).

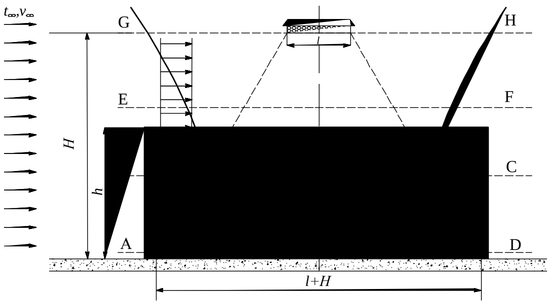
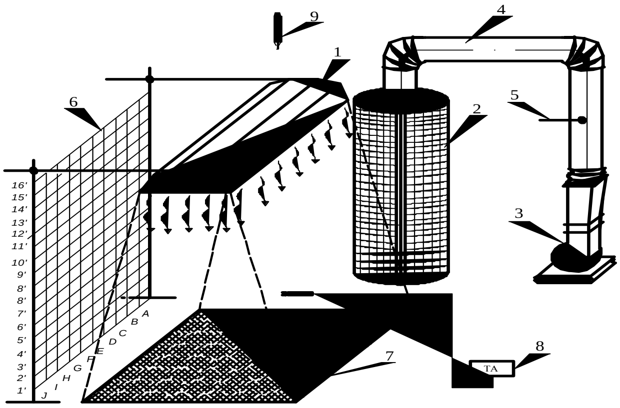


Fig.3. Schematic of convective flow distribution in the premise's production area:
H – Mounting height of the heater; *h* – height of the premise's production area; l – width of the heater; l+*H* – width of the irradiated area

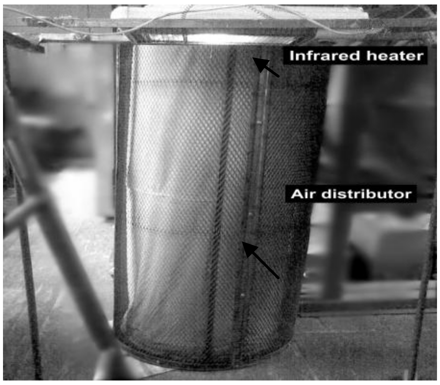
The produced convective flow contributes to an intensive movement of cold air masses with the temperature t_∞, ºC and velocity v_∞, m/s over the irradiated area, with the cold air masses being directed from the entire premise space to the production area. Therefore, the investigations have dealt with the determination of the air velocity on the temperature regime when using infrared heating. Solving this problem makes it possible to determine an acceptable movement of air in the premise's production area, which will cause the occurrence of a forced convective flow, but will not impact the air temperature reduction over the irradiated area.

II. EXPERIMENTAL INVESTIGATIONS

Investigations into the temperature regime in the production area have been performed on an experimental setup, the diagram of which is shown in Fig. 4.



(a)



(b)

Fig.4. Schematic of the experimental setup for investigating the air temperature above the infrared heater-irradiated area:
(a) Diagram of the experimental setup; (b) photo of the experimental setup
1 – Infrared heater NL-12R; 2 – air distributor; 3 – air supply fan; 4 – air supply duct; 5 – damper; 6 – coordinate grid; 7 – irradiated area; 8 - thermo-anemometer ATT-1004; 9 – Meteorological thermometer TM 6

The experimental investigation has been performed as follows [18]. In the first phase of investigations the material of the floor surface in the production area has been selected – a black metal surface having a specific characteristic of this material, blackness degree, *e* = 0.92. The electric infrared heater (1) of NL-12R type has been placed at the height *H*=1.72 m. The heater has been connected to the electric mains and switched by a switch key to the power *Q*=400 W, and then has been brought to the stationary mode of operation (5–10 minutes). Then the air supply fan (3) has been connected to the electric mains. A uniform air supply over the irradiated area (7) has been ensured through the air distributor (2) with the help of the supply duct (4). The supply airflow rate has been maintained at a stable level by the damper (5) so that the air velocity in the air distributor (2) outlet has been v_∞=0.1 m/s. The background air temperature t_∞, ºC in the premise has been measured by the meteorological thermometer (9). The temperature and velocity of the air over the irradiated area (7) have been measured by the thermo-anemometer (8) in the typical points behind the coordinate grid (6). The trial has been repeated three times in each point. The infrared heater capacity has been changed to 800 W and 1200 W, and the trials have been repeated. Similar investigations have been carried out at the heights H=1.5 m and H=1.28 m. Also, the experiments have been carried out on other types of surfaces such as wooden surfaces with the blackness degree e = 0.75; soil surfaces with the blackness degree e = 0.3. In the next investigation phases, the airflow rate in the air supply duct (4) has been changed by the damper (5), and the air velocity in the air distributor (2) outlet has been equal to v_∞ = 0.15 m/s and v_∞ = 0.2 m/s. Based on the known values of the heating capacity, design dimensions and mounting height of the infrared heater, the irradiation intensity has been determined by the following formula

$$I = \frac{Q}{S}, \text{ W/m}^2, \quad (1)$$

where Q is the heating capacity of the infrared heater, W; and S is the irradiated area, m^2, Equation (1) has been determined by the following formula [15].

$$S = (l + H)\cdot(m + H), \text{ m}^2, \quad (2)$$

In equation (2) l is the heater width, m; m is the heater length, m; H is the mounting height of the infrared heater, m.

The measurement errors have been determined by calculating the errors of parallel trials [17]. Analysis of the measuring system errors is shown in Table 1.

Table 1. Determination of measurement errors

Name of the element measured	Absolute error	Relative error	
		Min, %	Max, %
Background air temperature in the premise (meteorological thermometer, TM-6)	±0.03 ºC	0.2	0.37
Air temperature above the irradiated area (thermo-anemometer ATT-1004)	±0.13 ºC	0.18	1.7
Air velocity over the irradiated area (thermo-anemometer ATT-1004)	±0.005 m/s	0.6	1.25

The known methods of mathematical statistics have been applied to design the experiment and determine the impact of input factors on the temperature formation. The relative air temperature $\bar{t}_{air}$ above the irradiated area has been considered as a response function y, with the former being determined by:

$$\bar{t}_{air} = \frac{t_{air}}{t_\infty}, \quad (3)$$

In equation (3) t_{air} is the experimentally determined air temperature above the irradiated area, ºC; t_∞ is the background air temperature in the premise, ºC. The infrared heater irradiation intensity I, W/m^2 (x_1), and the degree of the irradiated surface blackness ε (x_2) have been chosen as variable factors x. The values of factors affecting the temperature regime formation at the stable air velocity in the premise v_∞ = 0.1 m/s have been determined by the method of rapid convergence. Within the basic level of the factors, the experiment has been designed and performed in order to obtain a mathematical model of the temperature regime formation process in the form of a second order polynomial

$$y(a, x) = a_0 + a_1x_1 + a_2x_2 + a_3x_1^2 + a_4x_2^2 + a_5x_1x_2, \quad (4)$$

where $a_0,..., a_5$ are the regression equation coefficients.

Refer to (4), to estimate the coefficients of the model which contain the functions of the independent variables of type x_i^2 (i is the factor number), the design's independent variable should have had three different values at least. A composite design for quadratic models has been obtained by adding a certain quantity of special points to the "kernel" obtained through a full factorial experiment. The 2n designs, where n is the number of factors, have been used as a "kernel". If the kernel is added with both a design center point having coordinates 0, …, 0 and with 2n so named "star" points having coordinates (±α, 0 ,…, 0), …, (0, …, 0, ±α), where α is the arm of star points, a central composite design is obtained [6], as shown in Table 2.

Table 2. Factors and their variability levels

Name of factor	Coded notation	Factor levels			interval of variability
		x_i = -1 (star point, lower level)	x_i=0 (basic level)	x_i = +1 (star point, upper level)	
Irradiation intensity I, W/m^2	x_1	85	276	467	191
Degree of blackness ε	x_2	0.3	0.61	0.92	0.31

The first value of each factor has been corresponding to its minimum value being denoted as -1, the second one has been corresponding to the average value being denoted as 0, and the third one has been corresponding to the maximum value being denoted as +1 (Table 3).

In constructing the composite designs, the value α has been chosen so as to ensure orthogonally of the design obtained. The value α has been determined by the formula [6]:

$$\alpha = \sqrt{2^{\frac{n}{2}} - \left(\sqrt{N} - 2^{\frac{n}{2}}\right)}. \quad (5)$$

Refer to (5): N is the total number of trials.

To ensure orthogonally, the model (4) has had to be transformed as follows:

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$$y(a,x)=b_0+a_1x_1+a_2x_2+a_3\left(x_1^2-\beta\right)+a_4\left(x_2^2-\beta\right)+a_5x_1x_2 \,. \qquad (6)$$

Refer to (6), the coefficient β has been determined as follows [6]:

$$\beta=\frac{\sum_{j=1}^{N}\left(x_i^j\right)^2}{N}=\frac{2^{n-p}+\alpha^2}{N}, \qquad (7)$$

In equation (7) j is the trial number; 2^{n-p} is the number of points of the composite design kernel.

It is easy to go from the model (6) to the model (4), with the coefficient a_0 being determined as follows:

$$a_0=b_0-\beta\sum_{i=1}^{n}a_{n+i} \qquad (8)$$

Refer to (8) the coefficient b_0 has been determined by the formula:

$$b_0=\frac{1}{N}\sum_{j=1}^{N}\overline{y^j} \,. \qquad (9)$$

In equation (9), $\overline{y_j}$ is the average value of the state variable y according to k parallel investigations:

$$\overline{y^j}=\frac{1}{k}\sum_{r=1}^{k}y_r^j \,, \qquad (10)$$

Refer to (10) k is the number of parallel investigations which have been performed under the same temperature regime; r is the investigation number.

Matrix F of independent variable functions for the orthogonal central composite design has had the shape shown in Table 3. The factious variable at the coefficient a_0 has been denoted by x_0.

The necessary number of trials has been estimated by:

$$N=2^n+2n+1, \qquad (11)$$

In equation (11) 2^n is the number of star points.

Therefore, the number of trials has equaled N=9. For this number of trials the values have been as follows: α = 1, β = 0.667 [6]. To estimate the influence of the indicated factors, a full factorial experiment has been carried out involving nine trials.

Table 3. Design of the experiment, matrix F and investigation results

	Trial umber	Parallel investigations k			$\bar{y}$
		y_1	y_2	y_3	
Kernel of the design (2^n design)	1	1.43	1.46	1.46	1.45
	2	1.046	1.057	1.035	1.046
	3	1.359	1.357	1.352	1.356
	4	1.025	1.032	1.018	1.025
Star points	5	1.21	1.26	1.25	1.24
	6	1.35	1.34	1.33	1.34
	7	1.357	1.355	1.35	1.354
	8	1.178	1.181	1.175	1.178
Center of the design	9	1.234	1.27	1.234	1.246

The regression equation coefficients have been determined by:

$$a_i=\begin{cases} c_1\sum_{j=1}^{N}x_j^i\overline{y}^j, & i=1,\dots,n,\\ c_2\sum_{j=1}^{N}[(x^j{}_{i-n})^2-\beta]\overline{y}^j, & i=n+1,\dots,2n,\\ c_3\sum_{j=1}^{N}x^j{}_{\mu}x_{\lambda}^j\overline{y}^j, & \mu,\lambda=1,2,\dots,n,\ \mu\neq\lambda,\ i=2n+1,\dots,k. \end{cases} \qquad (12)$$

In equation (12) c_1..., c_3 are the elements of the variance matrix at N = 9: c_1 = 0.1667; c_2 = 0.5; c_3 = 0.25.

The regression equation coefficients have been determined by the formulas (8) and (12) and have equaled: a_0 = 1.3; a_1 = 0.106; a_2 = 0.049; a_3 = –0.03; a_4= – 0.053; a_5 = 0.018.

By transforming the formula (6) into the formula (4), the regression equation has been obtained:

$$y(a,x)=1.3+0.106\,x_1+0.049\,x_2-0.03x_1^2-0.053\,x_2^2+0.018\,x_1x_2 \qquad (13)$$

In each line of the design matrix, the average values of variance according to three performed parallel trials have been estimated (Table 4) by the formula:

$$D=s_j^2=\frac{1}{k-1}\sum_{j=1}^{N}(y_i^j-\overline{y}^j)^2 \,. \qquad (14)$$

Table 4. Calculation of the variance of optimization parameter refer to (14)

№	$\bar{y}$	s_j^2
1.	1.45	0.0003
2.	1.046	0.000121
3.	1.356	0.000013
4.	1.025	0.000049
5.	1.24	0.0007
6.	1.34	0.0001
7.	1.354	0.000013
8.	1.178	0.000009
9.	1.246	0.000432

To check the variance homogeneity against the Cochran`s test, the relationship between the maximum variance and the sum of all variances has been established by the formula:

$$G_p=\frac{s_{j\,max}^2}{\sum_{j=1}^{N}s_j^2} \,. \qquad (15)$$

Refer to (15) with the numbers of freedom degrees f_1 = k – 1 = 2 and f_2 = N = 9 and with the significance level p = 0.05, the critical variance ratio has been G_{1-p} = 0.403 [8],

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which has exceeded the calculated value G_p = 0.4. In this case the calculated variance has been homogenous.
The average variance has been taken to estimate the reproducibility variance:

$$s^2_{\text{repr}} = \sum_{j=1}^{N} s_j^2 / N \, . \qquad (16)$$

To estimate the significance of regression equation coefficients, the variance of coefficients has been determined refer to (16), based on the known calculated value $s^2_{\text{repr}} = 0.000193$:

$$s^2_{bj} = \sum_{j=1}^{N} s^2_{\text{repr}} / (N \cdot k) \, . \qquad (17)$$

Refer to (17) significance of the coefficients has been determined against the Student's test. The determined value of the T_{1-p} – test has been compared with a tabulated value at the set significance number p = 0.05 and the corresponding number of the degrees of freedom $f_3 = N\,(k-1) = 18$, and has been T_{1-p} = 2.101 [8].

The *T*-ratio of each coefficient to its variance has been calculated to obtain $s_{bj} = 0.00267$: T_0 =487; T_1 =39.7; T_2=18.4; T_3=11.2; T_4=19.9; T_5=6.7.

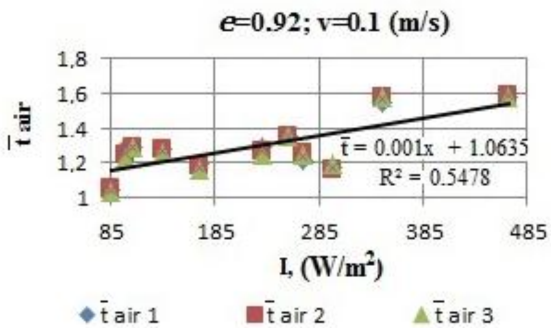
All the regression equation coefficients have been significant since $|T_{bj}| > T_{1-p}$.

Similar investigations have been performed at the air velocity in the premise's production area v_∞=0.2 m/s. The following regression equation has been obtained:

$$y(a,x) = 1.115 + 0.04 x_1 + 0.008 x_2 - 0.006 x_1^2 - 0.0121 x_2^2 - 0.0042 x_1 x_2 \qquad (18)$$

III. RESULTS

Air temperature above the irradiated area versus air velocity curves Experimental investigations into the air temperature above the area irradiated by the infrared heater has been performed. As the trial has been repeated three times in each point, the average value of the relative air temperature has been determined taking into consideration three parallel trials. Approximation of investigation results has been fulfilled for every trial, and the characteristic curves and approximation equations with its certainty values have been obtained (Fig. 5, 6, 7).



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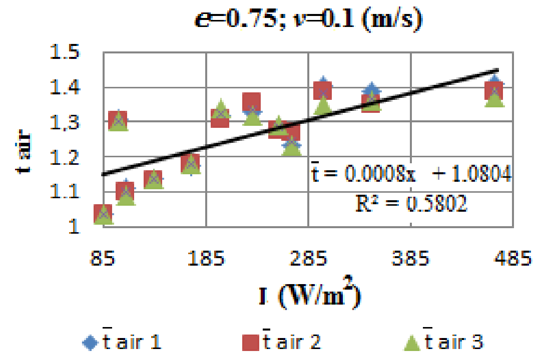

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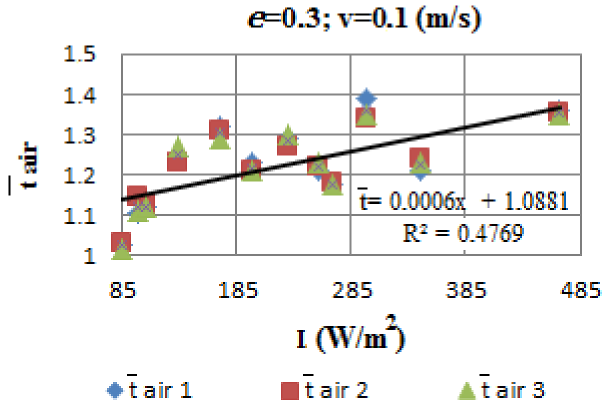
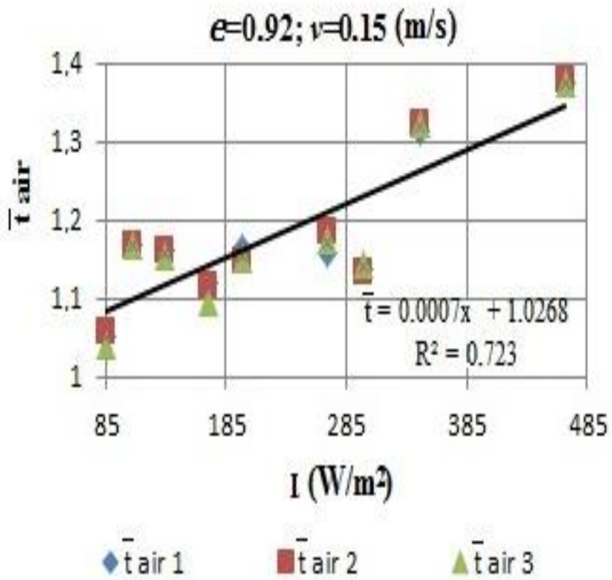


(c)

Fig.5. Experimentally found dependences of the relative air temperature $\bar{t}_{\text{air}}$ on the irradiation intensity *I*, W/m² at the air velocity over the irradiated area v_∞=0.1 m/s
(a) Degree of blackness *e*=0.92; (b) degree of blackness *e*=0.75; (c) degree of blackness *e*=0.3
R^2 – value of approximation reliability



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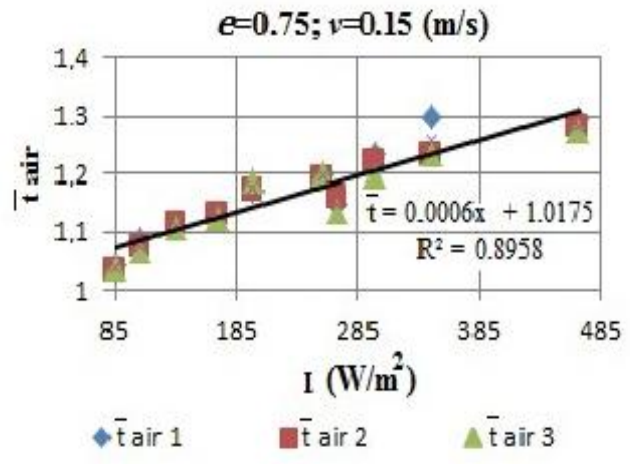

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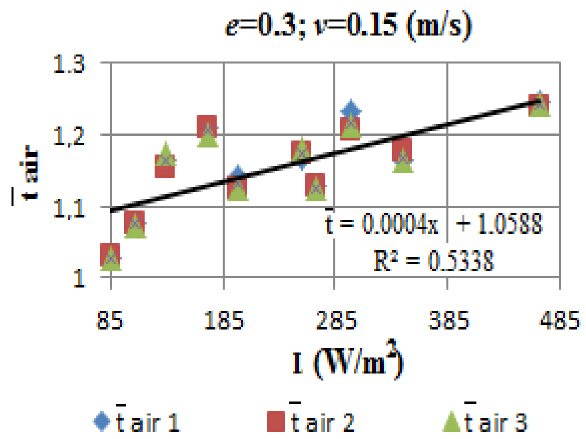
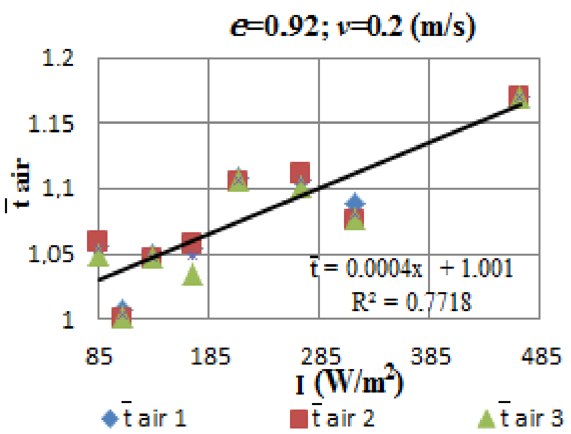


(c)

Fig. 6. Experimentally found dependences of the relative air temperature $\bar{t}_{air}$ on the irradiation intensity *I*, W/m^2 at the air velocity over the irradiated area v_∞=0.15 m/s

(a) Degree of blackness *e*=0.92; (b) degree of blackness *e*=0.75; (c) degree of blackness *e*=0.3

R^2 – value of approximation reliability



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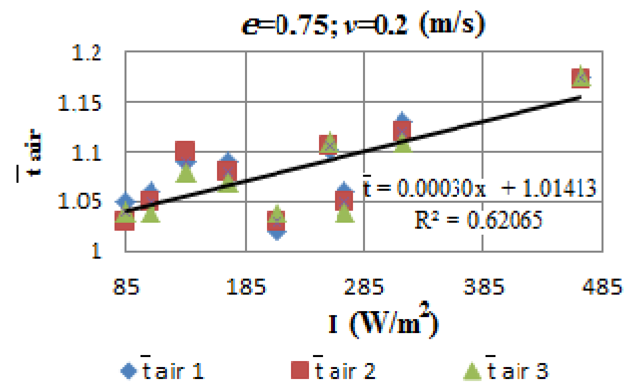

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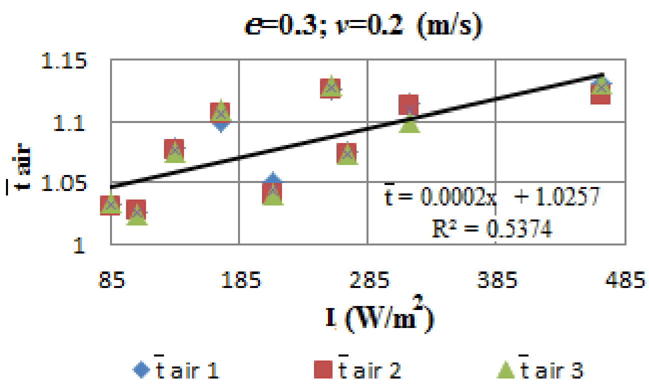

(c)

Fig.7. Experimentally found dependences of the relative air temperature $\bar{t}_{air}$ on the irradiation intensity *I*, W/m^2 at the air velocity over the irradiated area v_∞=0.2 m/s

(a) Degree of blackness *e*=0.92; (b) degree of blackness *e*=0.75; (c) degree of blackness *e*=0.3

R^2 – value of approximation reliability

Empirical dependences for determining the temperature regime over the irradiated area To determine the temperature regime over the area irradiated by the infrared heater, the statistical methods of investigation have been used. The performed experimental investigation has allowed obtaining the empirical dependences for determining the relative air temperature $\bar{t}_{air}$. The variation limits of input factors have been changing as follows. For the irradiation intensity – 85 W/m^2 $\le I \le$ 467 W/m^2; for the degree of blackness – 0.3 $\le \varepsilon \le$ 0.92.

The empirical dependence for determining the relative air temperature over the irradiated area at the air velocity v_∞ = 0.1 m/s, based on the equation (13), has been as follows

$$\bar{t}_{air} = 1.3 + 0.106\frac{I-276}{191} + 0.049\frac{e-0.61}{0.31} - 0.03\left(\frac{I-276}{191}\right)^2 - 0.053\left(\frac{e-0.61}{0.31}\right)^2 + 0.018\frac{I-276}{191}\cdot\frac{e-0.61}{0.31} \qquad (19)$$

Based on the regression equation (18), taking account of the previously taken variability intervals for input factors at the air velocity over the irradiated area v_∞=0.2 m/s, the

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empirical dependence has been obtained to determine the relative air temperature:

$$\bar{t}_{air} = 1.115 + 0.04\frac{I-276}{191} + 0.008\frac{e-0.61}{0.31} - 0.006\left(\frac{I-276}{191}\right)^2 - 0.0121\left(\frac{e-0.61}{0.31}\right)^2 - 0.0042\frac{I-276}{191}\cdot\frac{e-0.61}{0.31} \quad (20)$$

Estimating the critical values of the air temperature above the irradiated area Fig. 8 shows the diagram refer to (19) for determining the relative air temperature above the irradiated area.

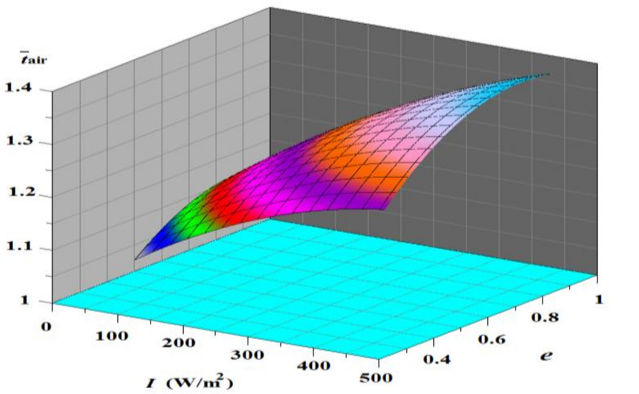

Fig.8. Surface of the response function at the air velocity v_∞=0.1 m/s

The diagram analysis has shown that an increase in the irradiation intensity value and blackness degree causes the relative air temperature above the irradiated area to rise. When the background air temperature in the premise is t_∞= 18ºC, the air temperature above the irradiated area is t_{air}= 25.0ºC for the maximum values of input factors, and t_{air}=19.4ºC for the minimum values of input factors. A similar way has been used to determine the critical values of the air temperature above the irradiated area $\bar{t}_{air}$ at the air velocity v_∞=0.2 m/s, refer to (20) (Fig. 9).

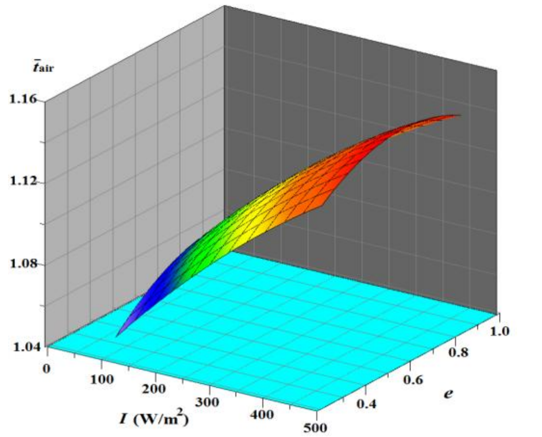

Fig.9. Surface of the response function at the air velocity v_∞= 0.2 m/s

When the background air temperature in the premise is t_∞=18ºC, the air temperature above the irradiated area is t_{air}=20ºC for the maximum values of input factors, and t_{air}=18.8ºC for the minimum values of input factors. Comparative analysis of these response surfaces shows that an increase in the air velocity in the premise causes the air temperature above the irradiated area to drop.

IV. CONCLUSION

This paper discusses the results of extensive parametric investigations into the temperature regime of a production area with infrared heaters being used. Obtained are the characteristic curves and empirical dependences of the air temperature above the infrared heater-irradiated area on the irradiation intensity and the blackness degree of the irradiated surface at various air velocities within the production area. The results of experimental investigations have shown that an increase in the air velocity over the irradiated area causes the air temperature to drop. This indicates an increase in the intensity of forced convective flow over the irradiated area. To prevent this phenomenon, it is necessary to expand the production premise's area being heated by the infrared heaters. Experimental investigations into the air temperature above the irradiated area have demonstrated the realistic results. This is evidenced by the results of testing the mathematical models for adequacy, the dispersion homogeneity of parallel trials and the significance of regression equation coefficients. The results of the investigations can be used in the engineering design of heat supply systems for production premises, based on the infrared heaters, as well as designing the radiant heating systems in buildings and facilities used for industrial and agricultural purposes.

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