MATHEMATICAL MODEL OF FILTERED INSULATION FOR HIGH-TEMPERATURE INSTALLATION

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Received: 10 February 2023/ Accepted: 15 March 2023/ Published: April 2023

Abstract: *A large amount of heat in the combustion of fuel in a high-temperature furnace is lost through the external fencing and heats up the smoke. Hence, reducing heat loss through the external fencing is necessary to save fuel, natural resources. This study provides the results of a mathematical model of heat transfer on a special surface relief in the air channels of the external walls of a high-temperature installation containing heat transfer intensifiers to improve fuel combustion efficiency.*

Keywords: *Heat transfer, filtered insulation, air channels.*

1. Introduction

Natural resources are very important in the economic development of each country in the world. However, along with the socio-economic development, the world's natural resources are facing the risk of depletion. Once the natural resources accumulated for billions of years are exhausted, there is no way to regenerate them, especially fossil energy sources. Every year, in smelters, glass-making furnaces, or large-capacity boilers in thermal power plants, a large amount of coal and gas fuels is used, of which only a part of the energy is obtained from the process. Since the combustion of the fuel is converted to the melting of the material, mixture, or heat-conducting medium, it is important to reduce the value of its unused portion. A significant proportion of unused energy is lost through the enclosures of high-temperature equipment and out through the exhaust gas. So, in modern furnaces, only 70% of the energy is used in the smelting process. Of this 70%, only 40% of the energy obtained from the combustion of the fuel goes to the smelting process, while 60% is lost through the external fencing and heats up the smoke.

The reduction of heat loss through the external fencing is usually ensured by its tightness, and the lowering of the heat transfer coefficient by selecting the appropriate insulation or by using a filtered insulation to heat the cold air, resulting in the heating of the cold air, heat materials, mix or burn.

The most important research results in thermal energy in this area are reflected in the works of Motulevich V. P and Sergievsky E. D [1, 6-9]; Goryunova I.Yu. [10]; Krylov A. N. [11-13]. These works focused on the effectiveness of using insulation filters in the external walls of high-temperature equipment, revealing differences in calculation methods and inconsistencies in specific results. It turns out that the source of the contradiction was the assumptions and simplifications that the authors used to study and come up with solutions describing heat transfer in porous materials.

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Therefore, the use of equal conditions for the temperature of the heat carrier and the temperature of the wall material can avoid a detailed description of its structural diversity. However, it raises a new problem. Its qualitative analysis shows a number of issues as follows:

First, the supply of thermal radiation to a thermally transmitted wall may result in the fact that the temperature on its opposite side may become higher than the average temperature of the permeable air at the outlet of the wall. Therefore, the increase in air temperature that occurs in this case must be accounted for by a separate heat transfer device.

Second, radiation absorption of a porous material does not occur in its boundary layer, but in its entire volume. This must be taken into account when forming a model describing the heat transfer processes in such a material.

Therefore, it is necessary to improve the calculation methods of the insulation filter, because it allows us to determine the energy savings in the heating process, leading to an increase in the energy efficiency of the devices performing this process.

2. The proposed solution

We study the solutions for the aforemention problems with respect to three cases:

2.1. The first case

Determining the possibility of using the marginal condition to calculate the heat loss through the outer layer of the ventilation channel according to the original data of [2].

Figure 2 shows a ventilation channel with values used to calculate temperature and heat flux.

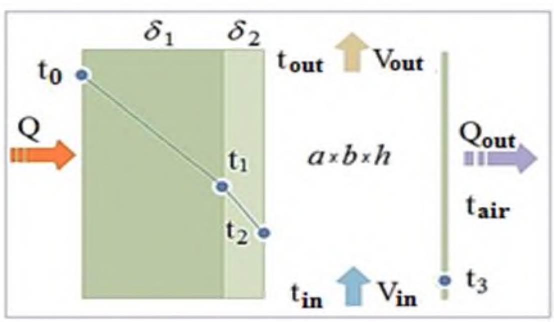

Fig.2. *Ventilation channel between the lining and the casing*

2.1.1. Initial data

Air channel parameters: Width a = 0.02m; length b = 0.4m; height h = 10m.

Casing parameters: Material -Al: thickness δ_{Al} = 0.005 m; coefficient of thermal conductivity λ_{Al} = 200 W/(m.K); emissivity ε_{Al} = 0.3;

Parameters of the walling layers: thickness of layer 1 and layer 2: δ_1 = 0,3 m, δ_2 = 0,1m; Thermal conductivity coefficients of the first and second layers $\lambda_1(t) = 2,1 + 0,0019 \cdot t_m$, $\lambda_2(t) = 0,33 + 0,00035.\ t_m$; Temperature of the inner surface of the brickwork $t_0 = 1500^0$C.

The air parameters at the entrance of the channel: the volume flow rate V_{air} = 0,03 m^3/s; Temperature $t_{air} = 20^0C$.

Approximate channel emissivity over an infinitely extended range of parallel surfaces:

$$\varepsilon_e = (1/\varepsilon_{Al} + 1/[\varepsilon_w \leftarrow 0.9] - 1)^{-1};$$

Ambient temperature $t_{Am} = 20^0C$.

2.1.2. Calculation part of the algorithm

Functions to calculate the thickness of hydrodynamic and thermal layers:

$$\left.\begin{aligned} \delta_T &= 5xRe_x^{-1/2} \\ \delta_N &= \delta_T Pr_{air}^{-1/3} \end{aligned}\right\} if\ Re_x \le 5\cdot 10^5$$

$$\delta_T = 0.37xRe_x^{-1/5} if\ Re_x > 5\cdot 10^5$$

Functions to calculate the local value and mean of Nusselt's numbers [3]:

$$Nu_x = \begin{cases} 0.332Re_x^{1/2}Pr_{air}^{1/3}\ if\ Re_x \le 5\cdot 10^5 \\ 0.0288Re_x^{0.8}Pr_{air}^{1/3}\ if\ Re_x > 5\cdot 10^5 \end{cases}$$

$$Nu = \begin{cases} 0.6642Re_x^{1/2}Pr_{air}^{1/3}\ if\ Re_x \le 5\cdot 10^5 \\ 0.036Pr_{air}^{1/3}(Re_x^{0.8} - 23200)\ if\ Re_x > 5\cdot 10^5 \end{cases}$$

Below is a system of balanced equations describing the heat transfer through the outside of a high-temperature furnace in the presence of a longitudinal ventilation channel with an approximation at the non-contiguous boundary layer and a model with parameters. concentration number. Direction of air movement in the channel from bottom to top:

Heat balance of the air passing through the channel:

$$\alpha_{[\text{Кр}]}\left(h, \theta_2, \theta_{air}, \frac{V_{air}}{a\cdot b}\right)(\theta_2 - \theta_{air}) + \alpha_{[\text{Кр}]}\left(h, \theta_3, \theta_{air}, \frac{V_{air}}{ab}\right)(\theta_3 - \theta_{air}) = \frac{V_{air}}{h\cdot b}\cdot \rho_{air}\cdot C_{p.air}(\theta''_{air} - t'_{air}) \quad (1)$$

$$\theta_{air} = (\theta''_{air} + t'_{air})/2 \quad (2)$$

Thermal balance on the outer surface of the mattress:

$$\alpha_{[\text{Кр}]}\left(h, \theta_2, \theta_{air}, \frac{V_{air}}{a\cdot b}\right)\cdot(\theta_2 - \theta_{air}) + \varepsilon_e\sigma[\Theta_2^4 - \Theta_3^4] = \frac{t_0 - \theta_2}{\delta_1/\lambda_1 + \delta_2/\lambda_2} \quad (3)$$

Thermal balance for the outermost shell:

$$\alpha_{[\text{Кр}]}\left(h, \theta_3, \theta_{air}, \frac{V_{air}}{ab}\right)(\theta_3 - \theta_{air}) + \alpha_{[\text{Ку}]}(\text{"B"}, \theta_3, t_{air}, h, b) = \varepsilon_e\sigma[\Theta_2^4 - \Theta_3^4] \quad (4)$$

Equilibrate the specific heat flows through the buffer layers:

$$\lambda_1(t_0 - \theta_1)/\delta_1 = \lambda_2(\theta_1 - \theta_2)/\delta_2 \quad (5)$$

$$\frac{t_0 - \theta_1}{\delta_1/\lambda_1} = \frac{t_0 - \theta_2}{\delta_1/\lambda_1 + \delta_2/\lambda_2} \quad (6)$$

2.1.3. Calculation result:

The total thickness of thermal boundary layers according to the elevation of their junction (0.24m):

$$\delta_N\left(0.24, t_2, t_{air}, \frac{V_{air}}{a \cdot b}\right) + \delta_N\left(0.24, t_3, t_{air}, \frac{V_{air}}{a \cdot b}\right) = 0.02\ m$$

The sum of the thicknesses of the hydrodynamic boundary layers according to the heights of their junctions (0.32 m):

$$\delta_T\left(0.32, t_2, t_{air}, \frac{V_{air}}{a \cdot b}\right) + \delta_T\left(0.32, t_3, t_{air}, \frac{V_{air}}{a \cdot b}\right) = 0.02\ m$$

2.1.4. Remark of the first case

It is incorrect to use this approximation when the air moves in the channel from bottom to top, because at the stage of laminar flow regime, the closure of the thermal and hydrodynamic boundary layers. The force takes place at an altitude of 0.24 and 0.32 m, respectively.

2.2. The second case

The system of balanced equations describes the heat transfer through the outer layers of the furnace according to the rectangular narrow ventilation channel according to the model with concentrated parameters.

2.2.1. Initial data: same as in the first case.

The calculation part of the algorithm. The system of balanced equations (1) - (6) is used, in which the mean of the Nusselt numbers is calculated according to the formula of Petukhov and Gnielinskiy [4]

2.2.2. Calculation results

Table 1. *Quantities to be determined*

Quantity	Value
Air temperature coming out of the channel, °C	587.79
Lining junction temperature, °C	1.18 x10^3
Liner surface outside temperature, °C	364.06
Casing temperature, °C	286,66
Average air temperature in the channel, °C	303,89
Heat released to the surroundings, W	8.77 x10^3
Heat transfer coefficient in the channel, W/(m^2·K)	44.71
Coefficient of surface heat in the casing, W/(m^2·K)	8.22

2.2.3. Remark of the second case

At the outlet of the air channel, the temperature is large enough that it can lead to combustion or be used to heat the mix. The density of heat flux into the medium in the second case is lower than in the case without ventilation channels, when compared along the end or side walls of the furnace. However, the high temperature of the furnace shell exceeds the maximum allowable value according to current regulations.

3.3. The third case

The outer surface of the lining has a narrow channel, which in the wall contains holes (concave in the form of spherical caps).

3.3.1. Initial data

The initial dat is configured as the first case but we add the parameters of the holes (depth h_{de}= 0.01m, printed diameter d_{di} = 0.04 m) and their density f = 0.69.

The calculation is performed according to a one-dimensional model with concentration parameters, in which to describe the convective heat transfer according to the empirical formula of I.A. Popov [5] is used and in the radiant heat transfer is approximated according to parallel infinitely extended faces with a regular staggered arrangement of recesses (Figure 3).

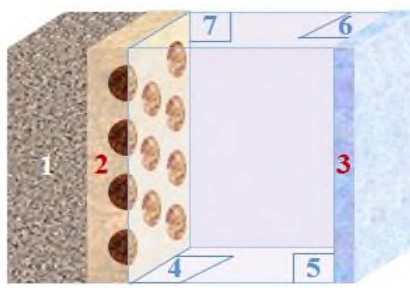

Fig.3. *External channel surfaces, participating in radiant heat exchange: 2-lining;3-casing*

In this case, the angular coefficient of radiation from the surface of the lining brick to the surface of the casing is determined by the formula

$$\varphi_{23} = 1/\left(1 - f + 4f \cdot \frac{h_{de}}{d_{di}}\right) \tag{7}$$

and the equivalent emissivity of the “Lining - Casing” system is expressed by the formula:

$$\varepsilon_e = \left[\left(\frac{1}{\varepsilon_3} - 1\right)\varphi_{23} + \left(\frac{1}{\varepsilon_2} - 1\right)\varphi_{32} + 1\right]^{-1} \tag{8}$$

In this case, the balanced equation system (1) - (6) is used, in which the expressions (7) - (8) and the empirical formula of Popov I. A [5] are used.

3.3.2. Calculation results

Table 2. *Quantities to be determined*

Quantity	Value
Air temperature coming out of the channel, °C	34.01
Lining junction temperature, °C	1.13×10^3
Liner surface outside temperature, °C	88.93
Casing temperature, °C	28.16
Average air temperature in the channel, °C	27.01
Heat released to the surroundings, W	106.97
Heat transfer coefficient in the channel, $W/(m^2 \cdot K)$	91.45
Coefficient of surface heat in the casing, $W/(m^2 \cdot K)$	3.28

3.3.3. Remark of the third case

When external channel surface of the narrow channel is used with holes (concave in the form of a spherical cap), the air temperature at the outlet of the channel is lower, but heat is lost to the outside environment through the enclosure (Heat radiated to the surroundings) is much lower.

The use of ventilation channels and concave bridges enhances heat exchange on the outer surface of the lining resulting in a significant reduction of heat loss to the environment. The low value of the air temperature at the outlet of the channel, which can be explained by the high air velocity, must be given for use in experimental studies [5].

4. Conclusion

The test is made based on the acceptance of using the boundary layer approximation in the calculation of heat loss through the enclosure of high-temperature equipment with ventilation channels.

Proven effectiveness of using enhanced heat transfer in the insulation filter system to increase the performance of high-temperature equipment.

In the future, it is necessary to: Simulate heat transfer in the outer layer of the channel with insulation filtering, taking into account the mechanism of absorption of thermal radiation, filtering of the heat carrier and the presence of a “heat jump degrees” at the porous material boundary; Develop recommendations to reduce heat loss and save fuel.

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