Air breathable thermal insulation with heat transfer intensifiers for high-temperature installation

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Abstract. To increase the efficiency of the high-temperature installation (HTI), several design options for air-permeable insulation in the outer furnace body are considered, differing in the location of heat-exchange intensifiers (HEI) - dimples in the form of spherical segments. As a result of a computational experiment, an option was established in which the heat losses are minimal, and the temperature of the heated air directed to combustion is maximum.

1. Introduction

The formulation and solution of problems devoted to improving the energy effectiveness and reliability of high-temperature heat-engineering plants is especially important for countries with developing economies. In recent years, this has become significant due to the increase in consumption and the cost of minerals, the desire to be an energy and technology independent country in the context of the sanctions policy. The prudent use of fuel and the improvement of heat engineering processes in the heat power system is one of the possible solutions to the problems encountered on the way to a highly developed economy.

High-temperature installations (HTI) are energy-intensive units. The increase in their efficiency is carried out mainly due to the utilization of the heat of the flue gases and the reduction of heat losses through the external fencing. The latter is usually ensured by its tightness and lowering the heat transfer coefficient by selecting appropriate heat-insulating materials. There is another method [1] that allows you to increase the service time of the HTI walls and to reduce the heat losses through them. It is based on the use of breathable materials. Cold air passing through such a material heats up itself, cools the lining (a multilayer system of the fireproof and heat insulating materials) of the HTI and is sent to combustion. The higher the temperature of the air sent to combustion or heating the batch material, the more efficient the installation is. Therefore, it is proposed to use heat transfer intensifiers (HEI) in the form of dimples (spherical segments) to intensify heat transfer and increase the air temperature at the outlet of the channels placed inside the HTI walls.

The works [1-5] are devoted to the organization of directional injection through permeable sections of the HTI structure for the purpose of cooling heat-stressed sections. The use of air-permeable insulation in HTI provides not only thermal stability of structures. It helps to reduce fuel consumption per unit of production [3-5] and reduce heat losses going to the environment [3-5, 6]. For example, in the publication [3] it is stated that the use of porous insulation with the supply of a cooler-cold air towards the heat flow in the melting chambers reduces the heat flow through the fence by two orders of magnitude. In [7], a solution is proposed that allows improving the service conditions of the lining and implementing high-temperature air heating in the filtered layer without involving autonomous air
heaters. Parametric studies with various schemes for supplying a cooler to permeable insulation in the HTI enclosure are given in the works of Alimgazin A. Sh., Sergievsky E. D., Motulevich V. P. [8]. Experimental studies of heat transfer in a barrier with air-permeable insulation, performed by Goryunova I. Yu., Mitrokhin Yu. S. and Pereletov I. I. [1-5, 7], showed that when the cooler is fed normally to the permeable wall of the HTI fence, it is possible to:

- Intensify radiant heat exchange in the working chamber of the HTI due to air heated in the zone of filtered insulation, and air sent to combustion;
- Reduce specific fuel consumption by 2-3 times.
- Radically reduce the amount of heat flow to the environment.

In [9], an idea was proposed that can significantly improve the efficiency of using air-permeable insulation. To do this, you need to change the surface relief of the porous insert by applying hemispherical dimples. Unfortunately, this idea was not implemented in practice. As for mathematical modeling, according to the publication [10], this work was completed. However, the authors did not fully present either the model itself or the results of the calculation. An exception is the vector diagram of air movement along the new design of the porous insert [11] and a qualitative conclusion about a significant intensification of heat transfer caused by the formation of a stable vortex at the front part of the dimple, which contains a hole in the first third of its rear part.

Currently, the improvement (in the sense of increasing the efficiency) of heat exchange equipment is developing in the direction of using passive heat exchange intensifiers. A significant contribution to the solution of this problem was made by national scientists: Kiknadze G. I. and Leontiev A. I., Terekhov V. I. and Volchkov E. P., Belenky M. Ya. and Gotovsky M. A., gortyshov Yu. F. and Sergievsky E. D.A deeper understanding of the features of heat-dynamic processes occurring on surfaces with complex terrain was formed thanks to experimental and numerical studies of Munyabin K. L., Isaev S. A., Popov I. A., Chudnovsky Ya. P., Shelchkov A.V. and others. Important results for theory and practice were obtained by foreign researchers, such as Ligrani F. M., Khalatov A. A., Voskoboynikov V. A., and others.

However, there is still no unified theory that allows you to form and control the process of heat and mass transfer in accordance with the selected target function in a given range of operating parameters, taking into account the geometry of vortex heat transfer intensifiers and the density of their location on the surface.

Therefore, the research that clarifies the picture of the heat transfer process, the possibility of its intensification due to a special surface relief in the air channels of the external walls (EW) of the HTI, is relevant.

2. Statement of the task
The purpose of this study is to identify the feasibility of using dimples to intensify heat exchange in the HTI EW, as a result, to increase the energy efficiency of the HTI. Fig. 1 presents the options for outdoor enclosures HTI, of which it is necessary to determine the best aggregate of such values as the maximum value of the bulk temperature of the air coming from the channels EW for burning, the minimum value of the heat flux penetrating through EW into the environment and the minimum value of the temperature of the casing of HTI.

![Figure 1](image-url)
As seen in Fig. 1 these variants differ in heat exchange intensifiers and their location on the surfaces of air channels of HTI EW. In the first option, air moves in the channel between the lining, on which the dimples are located, and the HTI casing. In the 2nd option, air is supplied to the channel between the filtered (breathable) insulation containing the dimples with the bottom holes and the HTI casing. Moreover, the surface of the inner channel from the side of the HTI lining is smooth. In the 3rd option, unlike the 2nd option, there are HEI in the form of dimples on the surface of the lining.

**Heat and technical characteristics of the studied design options for external walls of HTI**

**1st option**
- Casing parameters: material-Aluminum; thickness $\delta_{\text{AI}} = 0.001$ (m); coefficient of thermal conductivity $\lambda_{\text{AI}} = 236$ (W/m/K); specific mass heat capacity $c_{\text{p, AI}} = 904$ (j/kg/K); density $\rho_{\text{AI}} = 2700$ (kg/m$^3$); emissivity $\varepsilon_{\text{AI}} = 0.29$.
- Parameters of the two material walling layers: 1 material-Zircon, thickness $\delta_z = 0.02$ m; coefficient of thermal conductivity $\lambda_z = 1.3 + 0.64 10^{-3} t_{\text{m}}$ (W/m/K); specific mass heat capacity $c_{\text{p, Z}} = (0.63 + 0.21.10^{-3} t_{\text{m}}) 10^3$ (j/kg/K); density $\rho_z = (3.48 - 3.83) 10^3$ (kg/m$^3$); emissivity $\varepsilon_z = 0.52 - 0.8$.
- 2 material-Mullite, thickness $\delta_m = 0.012$ (m); coefficient of thermal conductivity $\lambda_m = 1.12 + 0.445 10^{-3} t_{\text{m}}$ (W/m/K); specific mass heat capacity $c_{\text{p, M}} = (0.835 + 0.21.10^{-3} t_{\text{m}}) 10^3$ (j/kg/K); density $\rho_m = (2.34 - 2.52) 10^3$ (kg/m$^3$); emissivity $\varepsilon_m = 0.8 - 0.85$.
- Air channel parameters: length $a = 0.533$ (m); width $b = 0.161$ (m); height $h = 0.012$ (m);
- Temperature of the inner surface of the lining $t_{\text{lin}} = 1500$°C;
- The air parameters at the entrance of the channel: the volume flow rate $V_{\text{air}} = 0.01932$ (m$^3$/s); the temperature $t_{\text{air}} = 20$°C;
- Ambient temperature $t'_{\text{Amb}} = 15$°C;
- The parameters of the dimples: depth $h_d = 0.01$ (m), printed diameter $d_p = 0.04$ (m) and the density of their location $f = \pi d_p^2 / S_1 / S_2 = 0.69$. Here $S_1 = S_2 = 0.030176$ (m) – the transverse and longitudinal steps of the dimples.

Fig. 2 presents a geometric model of the 1st version of the external fence of the HTI.

**Second option**

In contrast to the 1st version of the construction of the outer fence, the second version has a thermal insulation material between the wall and the HTI casing. The air permeability of which is due to the presence of bottom holes in the dimples that have the form of ball segments. These are heat exchange intensifiers with a depth of $h_s = 0.01$ m, a printed diameter of $d_p = 0.04$ m and a bottom hole with a diameter of $d_h = 0.0035$ m. The density of the location of the dimples on the inner surface of the lining is the same as on the outer surface of the lining. T. The layer of air-permeable material (FI) is made of fireclay bricks with a coefficient of thermal conductivity $\lambda_{\text{fi}} = 0.84 + 0.581 10^{-3} t_{\text{m}}$ (W/m/K); specific mass heat capacity $c_{\text{p, fi}} = (800 + 0.32 t_{\text{m}})$ (j/kg/K); density $\rho_{\text{fi}} = 1700$ (kg/m$^3$); emissivity $\varepsilon_{\text{fi}} = 0.75$. The breathable material has a thickness of 0.012 m and divides the space between the enclosure and the casing into two channels: hot and cold. The volume flow rate of air and the temperature at which air enters the cold channel have the following values: $V_{\text{air}} = 0.01208$ m$^3$/s, $t_{\text{air}} = 20$°C; Other thermal characteristics of the 2nd design variant.
are identical to the ones the 1st design variant of HTI EW. Fig. 3 shows the geometric model of the 2nd version of the external fence of the HTI.

**Figure 3.** Geometric model of the 2nd version of the HTI external fence: 1-fireproof layer, 2-thermal insulation layer, 3-internal (hot) channel, 4-air-permeable insulation (API) containing dimples with a bottom hole, 5-external air channel, 6-casing

**Third option**

As for the 3rd variant of the design of HTI EW, its difference from the 2nd variant is the presence of heat exchange intensifiers on the surface of the HTI walling. Their parameters and density of location are the same as in the 1st version of the design of the HTI EW. The thermal characteristics of the materials used in the 3rd version are identical to the materials given in the 1st and 2nd versions of the design of the HTI EW. Fig. 4 shows a geometric model of the 3rd version of the external fence of the HTI.

**Figure 4.** Geometric model of the 3rd version of the HTI external fence: 1- fireproof layer; 2-thermal insulation layer, which contains dimples on the outer surface; 3-internal (hot) channel; 4-air -permeable insulation (API), containing dimples with a bottom hole; 5 - external (cold) channel, 6-casing

**3. Tool of simulation. Turbulence models**

Numerical modeling of heat transfer for all the considered options was performed in the PHOENICS program. In all three variants, boundary conditions of the 3rd kind are set on the outer surface of the HTI casing, which takes into account the temperature of the external (ambient) environment $t_{Am}=15^\circ C$ and the heat transfer coefficient $\alpha_{Am}=6 \text{ W/m}^2/\text{K}$.

In the contact area of different bodies, the ideal conditions of conjugation are set (equality of temperatures and flows), as well as the "sticking" condition (zero air velocity in the zone of its contact with the surfaces of solids). On the inner surface of the lining, boundary conditions of the 1st kind apply, and on the outer side of the HTI casing-of the 3rd kind. The cold air temperature at the entrance of the channels of the external fence of the HTI for all variants $t_{inlet}=20^\circ C$. The volume flow rate of cold air in the 0 and 1 versions of $V_{air}=0.01932 \text{ m}^3/\text{s}$, and in the 2 and 3 versions of $V_{air}=0.01208 \text{ m}^3/\text{s}$.

Heat transfer by convection and thermal radiation of surfaces in the air channels of the external fence of the HTI is taken into account using a linear source, in which the heat transfer coefficient takes into account both transfer mechanisms.

When constructing the grid, the Cut-cell method is used, according to which the workspace is divided into regions (areas that are bounded by the surfaces of bodies that have different properties). Each region contains a certain number of cells, the sizes of which are set manually or automatically. We used the 2nd method, based on the professionalism of the developers of the PHOENICS program and the experience of the scientific group of E. D. Sergievsky [12].
In addition, it is assumed that:

- Minor geometry features do not significantly affect the physics of the process under study;
- A rectangular grid is best suited for implementing the control volume method in the PHOENICS program;
- The required number of grid cells should be set based on the power of the personal computer, the shortest calculation time, ensuring its convergence and acceptable error of the desired values;
- Qualitative coincidence of the structure of the air flow in the channel containing surface heat exchange intensifiers with the data of the work of Maskinskaya A. Yu. [13] will ensure the reliability of the results obtained.

The following turbulence models were used: Chen Kim $k\varepsilon$ Low Re in the 1st option, Realizable $k\varepsilon$ in the 2nd and 3rd options. Under thermal calculations of the HTI walls with filtered insulation the following criterial parameters were identified: the value of heat losses through the HTI walls - $Q_{\text{loss}}$, the mass-average temperature of the air for combustion - $t_{\text{out}}$, and also the temperature of the HTI metal casing - $t_{\text{coat}}$. The results are presented in Table 1.

| № var | Variants of wall constructions for the HTI | $u_{\text{inlets}}, \text{m/s}$ | $t_{\text{inlets}}, ^{\circ}\text{C}$ | $t_{\text{outlet}}, ^{\circ}\text{C}$ | $t_{\text{coat}}, ^{\circ}\text{C}$ | $Q_{\text{loss}}, \text{W}$ |
|-------|------------------------------------------|-------------------------------|---------------------------------|---------------------------------|--------------------------|---------------------|
| 0     | Smooth outer lining and no permeable insulation | 10                            | 20                              | 139.30                         | 21.56                    | 2.16                |
|       | Dimples on the outer surface of the lining and no permeable insulation |                     |                                  |                                 |                          |                     |
| 1     | Smooth outer surface of lining and dimples with the bottom holes in permeable insulation | 10                            | 20                              | 175.58                         | 63.95                    | 26.74               |
| 2     | Dimples on the outer surface of the lining and dimples with the bottom holes in permeable insulation | 3                             | 20                              | 182.95                         | 21.7                     | 2.26                |
| 3     | Dimples on the outer surface of the lining and dimples with the bottom holes in permeable insulation | 3                             | 20                              | 193.35                         | 19.3                     | 1.30                |

As can be seen from the table, the best option that showed the lowest heat losses $Q_{\text{loss}}$ through the walls of the HTI is the 3rd option. Here, the air passes through an air-permeable insulation containing the dimples with bottom holes, heats up, becomes turbulent and, when interacting with the lining, takes away some part of the heat from it. The presence of dimples on the walls of the hot channel increases the intensity of heat exchange and, as a result, the air acquires a higher temperature. Leaving the hot channel, the air carries with itself a significant part of the heat which was not used in the other options considered and simply went out through the walls of the HTI.

Analysis of the structure of the air flow, which is formed in the channels of the three different options HTI EW, showed: In the case of the 1st variant, when the channel walls are lining and the casing HTI is observed return movement of the air in the dimples located on the outer surface of the lining, and also the cellular and circulating motion of the air in the dimples, and between them. This is clearly seen in Fig. 5 and 6.

According to Fig. 7, the maximum air velocity is observed at the outlet of the dimples in the area immediately adjacent to the surface of the dimples. As for the air temperature, it increases in the direction of flow and takes higher values between the dimples.
Figure 5. Vector and color diagram of the structure of the air flow between the lining and the casing (cross-section x=0.354 (m) in the first version of the design of HTI EW)

Figure 6. Vector and color diagram of the structure of the air flow between the lining and the casing (a fragment of the longitudinal section in the first version of the design of the HTI EW)

Figure 7. Distribution of temperature (a) and velocity (b) of air flow near the surface with dimples

The air flow structure, which is formed in the 2nd and 3rd versions of the design of the EW, differs from the first version. The main contribution to this difference is made by the air-permeable material that divides the space between the enclosure and the HTI casing into internal and external channels. The material has dimples with a bottom hole for blowing in cold air from one channel to another channel.

Fig. 8 compares the structures of fields formed in the channel, the walls of which correspond to the 2nd and 3rd versions of the external fence of the furnace. It can be seen that in the 2nd variant the edging of the vector field distribution is ellipsoidal, while in the 3rd variant it is conical. It was found that the average air temperature in the channel near the wall (in section Z=0.049 m) in the 2nd version (194°C) is less than in the 3rd version (210°C), and the average air velocity in the channel in the same section in the 2nd version (5.03 m/s) is greater than in the 3rd version (4.14 m/s). In addition, in the section Z=0.039 m (nearAPI), it is seen that the air from one hole flows into neighboring dimples.
located in the next row along the course of the air flow. This is indicated by the direction of the vectors.

![Flow structure in the channel between the lining and the air permeable insulation in the second and third variants of placement of surface heat exchange intensifiers in the HTI EW](image)

**Figure 8.** Flow structure in the channel between the lining and the air permeable insulation in the second and third variants of placement of surface heat exchange intensifiers in the HTI EW

Figure 9 shows the air velocity field in the cross-section of the channel. You can see the circulation of air, both in the dimples and between them. In the 3rd variant, as in the 2nd variant, air flows from one dimple to another dimple. In addition, in both versions of the design of the HTI EW, there are helical, circular and return movements of air in the channel, the walls of which have dimples (Fig. 10).

![Velocity field in the cross-section of the channel in the third version of the design of HTI EW](image)

**Figure 9.** Velocity field in the cross-section of the channel in the third version of the design of HTI EW

The biggest error among the determined values is the pressure, which in the 1st, 2nd and 3rd variants of the HTI external fence design does not exceed 0.003%, 1% and 1.4%, respectively.
Figure 10. Vector and color diagrams of the air flow between the lining and the air-permeable insulation, which correspond to the second (a) and third (b) versions of the design of the HTI EW

Conclusion

To increase the energy effectiveness of HTI, it is advisable to use air-permeable insulation with the bottom holes dimples which intensify heat exchange, so the air in the outer enclosure acquires a higher temperature. And further the air is used for preheating the batch material and / or for maintaining combustion in the burner devices, which leads to fuel savings in heat-technological processes.

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