The pulsations of boundary conditions – factor of the rapid wear on heat exchange surfaces in heterogeneous dispersed flows

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Abstract. The results of experimental studies of industrial furnace with a fluidized bed reactor. The data on the values of the coefficient of heat transfer, the quality of fluidization and mixing efficiency. In theory shows that there are significant variables of temperature gradients on the walls of the heat exchange elements are qualitative arguments about the causes of increased wear of heat exchange surfaces in a fluidized bed.

1. Introduction
In the present paper, we give some experimental data and theoretical justification of the research results furnace FB-450 Cherepovets chemical plant, part of the union "FosAgro" (formerly NOP "Ammofos"). Here is an overview of the furnace with a fluidized bed reactor. Furnace type FB-450 [1] is an element of the process of production and sulfuric acid are used for the exothermic roasting of pyrite (FeS₂), followed by sulfur dioxide yield (SO₂). The chemical reaction carried out in these furnaces is described by the following equation:

\[ 4FeS_2 + 11O_2 \rightarrow 2Fe_2O_3 + 8SO_2 + 3400 \text{kJ} \]  

(1)

The warm-thermal process conditions is produced by burning natural gas, and the temperature control in the layer (750 ÷ 800) °C in a process is provided mainly through the use of embedded in a layer of heat exchangers with a total area of 77 m². The internal volume of the oven - 450 m³. Airflow - 45 10³ m³/h. The experiments were conducted on two furnaces - № 4 and № 13. From the available data furnace 13 furnaces were chosen because one of them (the furnace №13) was equipped with an experimental blow the central unit (CUB) and the second (oven № 4) - normal. CUB is a tower located at the center and a gas distribution grid nozzles equipped in its upper and lower parts of the tangential air inlet to the fluidized bed. It was assumed that the introduction of said CUB priori motion intensifies solids in the layer significantly improve mixing coefficients and the external heat, and eventually - the furnace performance sulphide gas.

However, clearly visible and tangible positive results of the introduction of CUB has not given, therefore, to establish the feasibility of further use in other furnaces FB-450 was made a special study, in which not only solved the challenge, but also yielded important for the practice of side effects, concerning the reasons for the rapid wear of heat transfer surfaces. These results are discussed below.
2. Experimental equipment
The experimental part of the research carried out by the technique developed in the problem of the research laboratory of the Department of Thermal Physics of the Leningrad Institute of Precision Mechanics and Optics (LITMO, now – NIY ITMO), and under the overall supervision of prof., Doct. of Scien. (Tech) G.N. Dulnev [2,3]. The study determined the coefficient of heat transfer from the water-cooled steel probe (alpha-calorimeter – Figure 1)) to a boiling layer, the characteristic frequency of the pulsations porosity layer and the surface temperature of the probe (integrated quality sensor fluidization – Figure 2) in different parts of the layer and by different processing modes.

Figure 1. General view (a) and structure (b) alpha -calorimeter: 1 - body, 2 - RTD, 3, 6 - junctions of the thermocouples at the inlet and outlet of the coolant, respectively, 4 - protective glass, 5 - serving the coolant tube.

The heat transfer coefficient was calculated using the formula:

$$\alpha = \frac{G c_w (t_{\alpha}^* - t_{\alpha}^o)}{S_{\alpha} (T_B - T_W)}$$  \hspace{1cm} (2)

where: \( G \) - the mass flow of coolant (water), kg/s; \( c_w=4200 \text{ J/(kg K)} \) - specific heat capacity of water; \( t_{\alpha}^* \cdot t_{\alpha}^o \) - water inlet temperature and outlet alpha calorimeter respectively, °C; \( S_{\alpha}=9.3 \times 10^{-3} \text{ m}^2 \) - exterior surface of the working body alpha calorimeter; \( T_W \) - temperature of the outer surface of the alpha-calorimeter, K; \( T_B \) - the average temperature of the fluidized bed, K. The surface temperature \( T_W \) was measured using a platinum resistance thermometer. The thermometer has a nominal electrical resistance of 80 Ohm at 20 °C, the thermal time constant of the order of \( 10^{-2} \text{ s} \), the thermal coefficient of resistance \( 3.85 \times 10^{-3} \text{ K}^{-1} \) (in the temperature range 20-300 °C). In the experiment recorded parameters necessary to determine the heat transfer coefficient as well - the instantaneous values of the electrical resistance of platinum thermometer. The bed temperature \( T_B \) was determined as the average of four full-HA66-type thermocouples, the temperature difference \( (t_{\alpha}^* - t_{\alpha}^o) \) - on the thermoelectric force developed thermopile placed in alpha-calorimeter. Figure 3 is a diagram of sensing, as the table 1 shows the values of the coefficient of heat transfer between the bed and placed him in the probe. According to estimates done error in determining the heat transfer coefficient does not exceed 12%.

3. Experimental data
The main experimental results are presented in Table 1.
From the analysis of the results led to the following preliminary conclusions:
- maximum heat transfer coefficients observed at a distance of 0.2-0.3 m from the top of the layer and away from the inner wall surface - 2.0-2.5 m;
- the main contribution to the improvement in the external heat exchange brings the upper part of CUB and therefore no need for bottom CUB that resulted in a significant energy saving;
- the measured value of quality of fluidization [4,5] $\xi=25$ and mixing efficiency $\eta=32\%$, indicating that significant uneven mixing of the material in the layer and of a low-temperature firing zone and heat. In this regard, it is recommended to increase the mixing efficiency by introducing additional turbulence while redistribution air supply through a distribution grid;

Table 1. The main experimental results.

| Insertion of the probe $L$, m | The heat transfer coefficient $\alpha$, W/(m$^2$-K) | Operating mode CUB (oven number 13) |
|-----------------------------|-------------------------------------------------|-------------------------------------|
| 1.5                         | 336                                             | CUB completely open                 |
| 2.0                         | 731                                             | Top of CUB is open lower part       |
| 2.5                         | 884                                             | closed                              |
| 1.5                         | 426                                             |                                     |
| 2.0                         | 750                                             |                                     |
| 2.5                         | 888                                             |                                     |

- as a result of studies revealed the presence of low-frequency pulsation surface temperature probe having the frequency $f_T\approx10^{-3}$ Hz and an amplitude of the order of about 200 K. At this temperature layer $T_B$ during the measurement varied no more than 15 K, the temperature $t_w$ of the cooling water tube not more than 0.3 C. It is understood that such small changes in temperature $T_B$ and of themselves may not lead to significant changes in temperature of the probe surface alpha calorimeter. Apparently, this is the temperature fluctuations due to mixing layer. For illustration, in figure 4 shows a typical view of such oscillations in the case where $T_w=416$ °C;

![Figure 4](image4.png)

**Figure 4.** Kind of temperature fluctuations alpha-calorimeter surface.

- heat transfer surfaces, which are in a fluidized bed, are operated at a significant difference in coefficients of heat transfer from the layer to the surface ($\alpha_1$) and from the inner surface to the coolant (water) ($\alpha_2$). The coefficient of heat transfer $K$ (when neglecting the thermal resistance of the pipe wall) of the probe immersed in the fluidized bed is in the range:

$$K = \frac{\alpha_1\alpha_2}{\alpha_1 + \alpha_2} \approx 220 \div 250 \text{ (W/(m}^2\text{K})}$$  \hspace{1cm} (3)

- on the basis of measurements of the heat transfer coefficient, the analysis of the temperature fluctuations of this work the author considers it possible to put forward his version of explaining the reasons for the rapid wear of heat transfer surfaces in the system. Using the self-oscillating model...
approaches fluidized bed [6], it is logical to assume that the external heat transfer coefficient change over time due to gravitational fluctuations and uneven mixing layer by layer volume, cause time-varying thermal stresses that are close to critical for the material of heat exchanger tubes, and the thermal stresses can be cyclic, that is, changes its sign. These thermal stresses degrade the material's resistance to mechanical wear.

The main reason for these thermal stresses in a heat exchange element is the difference in heat transfer coefficient $\alpha_1$ and the coefficient $\alpha_2$ and the pulsating nature $\alpha_1$. This ripple coefficient of heat transfer $\alpha_1$ from the fluidized bed to the surface causing a significant temperature gradient in the wall of the heat exchange element, and they, in turn, accompanied by thermal stresses. Although this study does not attempt to find the connection between the pulsations of heat transfer coefficient (surface temperature) with the magnitude of thermal stresses arising in the wall, but the author believes it useful to show the presence of time-varying significant temperature gradients through the thickness of the walls of the heat exchanger. To demonstrate this, it was mathematically modeled, is to solve the following problem.

4. The physical formulation of the problem

There is unlimited in length plate of finite thickness $\delta$ (figure 5). The initial temperature distribution in the plate is uniform, the temperature is the average temperature measured in experiments surface in a fluidized bed. At timing plate begins $\tau=0$ to participate in heat exchange with the heat in these conditions at its surfaces: the heat transfer coefficient $\alpha_1$ corresponding to the coefficient of heat transfer in a fluidized bed at a temperature $T_B$ of - the outer surface of the plate and the heat transfer coefficient $\alpha_2$, corresponding to the heat transfer wall with the coolant (water), having a temperature $t'_w$ of - on its inner surface. The temperature of the coolant temperature is less than the fluidized bed $t'_w < T_B$. Heat transfer is described by Newton's law (boundary conditions of the third kind). Necessary to calculate dimensional unsteady temperature field in the plate across its thickness, i.e. $T(x,\tau)=t(x,\tau)$.

4.1. Assumptions made

1. The fluidized bed is considered as a medium whose properties can be described by effective physical characteristics: thermal conductivity $\lambda_{\text{eff}}$, density $\rho_{\text{eff}}$, specific heat capacity $c_{\text{eff}}$.
2. The wall is presented as unbounded along the plate.
3. Thermo-physical properties of the plate does not depend on the temperature.
4. Heat transfer coefficients $\alpha_1$, $\alpha_2$, for $\tau=0$ acquire a finite values and remain constant (stepwise impact).

4.2. The mathematical formulation of the problem is given.

\[
\begin{align*}
\frac{\partial^2 T(x, \tau)}{\partial \tau^2} &= a \frac{\partial^2 T(x, \tau)}{\partial x^2}, \\
-\lambda \frac{\partial T}{\partial x}\bigg|_{x=0} &= \alpha_1 \left( T_B - t_{w,\tau} \right), \\
-\lambda \frac{\partial T}{\partial x}\bigg|_{x=\delta} &= \alpha_2 \left( t_{w,\tau} - t'_w \right), \\
T(x,0) &= t_0
\end{align*}
\]

where $\lambda$ - the thermal conductivity of the wall material, W/(mK); $a$ - thermal diffusivity of the wall material, m$^2$/s.

4.3. Decision.

The task was solved by the operational method. Equations (4) after applying the Laplace transform takes the form:
The system of equations (5) in the general form:

\[
T(x,S) = \frac{t_0}{S} + A \cdot ch\left(\sqrt[2]{a} x\right) + B \cdot sh\left(\sqrt[2]{a} x\right)
\]

where the constants A and B are from the boundary conditions (4):

\[
T'(x,S) = A \cdot \sqrt[2]{a} \cdot ch\left(\sqrt[2]{a} x\right) + B \cdot \sqrt[2]{a} \cdot ch\left(\sqrt[2]{a} x\right)
\]

After substituting (8) into (4) the following expression for \(T(x,S)\):

\[
T(x,S) = \frac{t_0}{S} \left[ (a_i + b \cdot ch\left(\delta\sqrt[2]{a}\right) + c \cdot sh\left(\delta\sqrt[2]{a}\right) \right) + \frac{1}{2} \right] + \frac{b}{S} \cdot a \cdot sh\left(\delta\sqrt[2]{a}\right)
\]

where \(a_i = h_2(t_0 - t_W)\); \(b = h_1(t_0 - t_b)\); \(c = h_1 h_2(t_0 - t_b)\);

Applying inverse Laplace transform to equation (9) can be obtained by a general expression for \(T_W(x,\tau)=T(x,\tau)\):

\[
L^{-1}\left[\frac{t_0}{S} - T(x,\tau) - t_0 \right] = t(x,\tau) - t_0 = \frac{ch\delta^2 - \mu_n (a_i + b)}{\mu_n^2 (h_1 + h_2)} - \sum_{n=1}^{\infty} A_n \exp\left(-\frac{\mu_n^2 \alpha \tau}{\delta^2}\right) \times
\]

\[
\times \left[ a_i \cos\frac{\mu_n x}{\delta} \right] + \sin\frac{\mu_n x}{\delta} \left[ a_i \cdot h_1 \right] - \frac{b \delta}{\mu_n} \left( a_i - h_1 \right) + \cos\left(\frac{b - ch_2 \delta^2 / \mu_n^2}{2}\right) +
\]

\[
+ \cos\left(\frac{c - bh_2 \delta}{2\mu_n}\right) + \sin\left(\frac{c - bh_2 \delta}{2\mu_n}\right) + \sin\left(\frac{\delta - x}{\delta} \left( \frac{c - bh_2 \delta}{2\mu_n} \right) \right)
\]

where \(A_n = -\frac{2\mu_n \sin\mu_n}{\mu_n^2 (h_1 + h_2)(\cos\frac{\mu_n x}{\delta} + \mu_n^2 (\cos\mu_n + 2\delta h_2) + 2\delta h_2 \sin\mu_n = 0}
\]

As calculations for solving this problem it is sufficient to take advantage of engineering only the first term of the expansion in equation (10), i.e.:
Figure 7, the maximum rate of change of surface
temperature (τ=0) occurs at times of the order of 1-5 seconds. Exactly the same order and have the
pulsation periods of the microstructure of the layer caused by gravity. If the time since the beginning
of exposure of the thermal disturbance is 1-5 s with the temperature difference between the surface
plate according to the calculation amounts to 50 K (figure 6), which corresponds to the temperature
gradient of 10 K/mm. In this context and taking into account the provisions of the two-phase theory,
which states that the intensity of the heat transfer to the gas bubble approximately an order of
magnitude lower heat transfer to the package of particles, we can assume the presence of a heat
exchange element time-varying temperature gradients of considerable magnitude. It is obvious that the
equality of the coefficients of heat transfer α₁ and α₂ data gradients are minimal.

Strong difference in coefficients α₁ and α₂, apparently, to be present only in systems with small
particles (dp<10^{-3} m), which reach values α₁ of the order of 10^{3} W/(m² K) and above [7].

In this case, there is every reason to believe that the time-varying values of the wall temperature are
accompanied by a changing thermal stresses, which are one of the main reasons that reduce the
material's resistance to heat exchangers corrosive and erosive wear. Practical measures that can reduce
the influence of factors may be considered, for example, using a heat exchanger material with a higher
thermal conductivity, reducing the temperature gradient across the wall thickness due to the use of
heat exchange elements of the "tube in tube", increasing the heat transfer coefficient of the inner wall to the system for by increasing the flow rate, pressure, etc.

Found fact together with the known data of the temperature irregularity on the surface of the heat exchange elements [8] leads to the conclusion that existing designs superheaters and similar elements running in critical conditions, especially noticeably manifested in fluidized bed apparatuses used in high-temperature chemical technology.

5. Conclusions

Industrial Investigation apparatus - furnace FB-450 showed, that the swirlers are used in furnaces, or the so-called central blowing blocks intensify the process of external heat, in particular - to increase the heat transfer coefficient is 10-15%, while at the same time, separate zones layer degrade it. In this connection should be treated with extreme care to use these blocks. This requires complex analysis of the totality of all the processes not only in the layer, but in the other elements of the process equipment.

The observed experimentally large-scale temperature fluctuations on the surface of the metal probe (with an amplitude of up to 100 K), confirming the performance of mathematical modeling, and, apparently, is one of the reasons for the rapid wear of heat transfer surfaces in the fluidized beds. This phenomenon, according to calculations, should be observed only with a significant difference between the heat transfer coefficients on the outer and inner surfaces of the heat exchanger elements, so the practical measures to eliminate the negative impact of the wall temperature fluctuations should be based on the finding.

6. References

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