ANALYSIS OF THE EFFECT OF PERIODIC PULSATIONS OF LIQUIDS FLOW ON THE HEAT TRANSFERRING IN A CHANNEL WITH DISCRETE ROUGHNESS

АНАЛИЗ ВЛИЯНИЯ ПЕРИОДИЧЕСКИХ ПУЛЬСАЦИЙ ПОТОКА ЖИДКОСТИ НА ТЕПЛООБМЕН В КАНАЛЕ С ДИСКРЕТНОЙ ШЕРОХОВАТОСТЬЮ

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Abstract: *At the present days the great attention is given to a problem of research of hydrodynamics and heat exchange in the pulsating flows. Experimental studies for the flow in smooth channels show that the pulsation of fluids flow significantly affects to the heat transferring and can be accompanied by both reduction and increasing in the intensity of the heat exchanging. This problem has a big practical importance in the study of unstable processes in a various moving and power plants. The results showed that with unsteady fluid's flow with a alternating pulsations relative to the average velocity in a discretely rough channel is furthering to the intensification of the heat transferring. It is shown that flow pulsations significantly affecting on the heat transferring coefficient, and its average values. This fact opens up the possibility of using such currents to increase the energy efficiency of various technical devices.*

KEYWORDS*: HEAT TRANSFER ENHANCEMENT, DISCRETE ROUGHNESS, COMPUTER MODELING, NUMERICAL CALCULATION.*

1. Introduction

Much attention has been paid to the problem of studying of the effect of pulsating flows on hydrodynamics and heat transferring in recent years. Experimental studies of unsteady flows at the present day showed that such unsteady process can be accompanied by both reduction and increasing in the intensity of the heat exchanging [1].

Known results of experimental and theoretical [2] studies are often solutions for the specific problems and do not allow making broad generalizations about the level of influence of superimposed flow's pulsations on the intensity of heat transferring. At this moment, there is not enough reliable information about the kinematic structure of the pulsating flow in the channels under the conditions of superimposed nonstationarity.

Based on the reliability of information about the structure of the pulsating flow in the channel, it is possible to estimate the effect of superimposed pulsations on the heat transferring, as well as to identify patterns of changing in flow's characteristics under considered conditions.

This fact opening up the possibility of using such flows to increase energy efficiency in the studying of unstable processes in various moving and energy equipment.

Thus, obtaining information about the structure of the pulsating turbulent flow and identifying patterns of heat exchanging processes of such flows in discretely rough channels is urgent task for the present time.

The main goal of this work is to use computer simulation and numerical analysis to investigate the effect of periodic flow pulsations on the heat transferring in a channel with discrete roughness in the shape of hemispherical concavities.

2. Prerequisites and means for solving the problem

Analyzing of the existing literature has shown that there are extensive reviews of hydrodynamics and heat transferring studies in smooth and discretely rough channels with a stationary flow of coolant [2-5].

The heat exchange of a hydraulically smooth circular channel with a stationary developed turbulent flow has been studied in detail and well described by the M.A. Mikheev dependence [12] for various regimes of forced fluid flow in a smooth channel.

It is also known that increasing in the intensity of heat exchanging between the coolant and the heat exchange surface is provided, as a rule, with the help of discrete roughness, leading to the partial or complete destruction of the boundary layer, in which concentrated the greatest thermal resistance, as well as significant turbulization of the flow. These effects are achieved by the organization of flow's separation and attachment areas, an increase in the relative flow velocity near the wall, and generation of the pressure pulsations in the flow and other ways of influencing to the near-wall structure of the flow [6-8].

The experimental and theoretical results of the study of pulsating flows that exist today are mainly obtained only for the boundary layer and the flow in a smooth channel [9,10].

For the successful using of the detachable areas, it is necessary to know the mechanism of their interaction with the main turbulent pulsating flow and the mechanism of the processes in the detachable area itself. These processes are very complex.

At this stage, numerical research methods using the latest advances in the field of boundary layer diagnostics and computerization are the most effective way in the modern theory of heat and mass transferring.

In this work, in order to solve the heat transferring problem in a channel with discrete roughness in the shape of concavities with pulsating fluid motion, 3D modeling software complex CAD/CFD of SolidWorks / Flow Simulation is used.

With using the SolidWorks CAD software calculating and building three-dimensional geometric model of a discretely rough channel.

The numerical solution of the problem is performing in the Flow Simulation software, in which the motion and heat transferring of a fluid is modeling with using the Navier – Stokes equations [11], which describe in unsteady formulations the laws of conservation of mass, momentum and energy of a given medium. In addition, using equations of state of the components of the fluid, as well as the empirical dependences of the viscosity and thermal conductivity of these components of the medium on temperature.

Considering the complexity of the research task, the insufficiency and inconsistency of the existing well-known research results, it is necessary to determine the accuracy and reliability of the results of numerical calculations. For this purposes two main problems were solved:

- carried out series of calculations on the grids with different resolution of the geometric features of the model and non-linearity of the calculated physical parameters field to ensure that there is grid convergence of the solution to the problem and to obtain the final solution of the problem on the optimal (in terms of the accuracy of the mathematical problem solving taking into account computer resources and performance) of the computational grid.
- in a non-stationary problem formulation, perform time discretization for each cell of the computational grid in the computational area from the Kurant condition and determine the allowable maximum time step depending both on the values of physical quantities and the space discretization step in the cell area.

3. Solution of the examined problem

Computer simulation was carried out with using the CAD/CFD complex software SolidWorks / Flow Simulation. In the SolidWorks CAD software was constructed calculated three-dimensional model of a circular channel with discrete roughness in the shape of hemispherical recesses (concavities) with a sharp input and output edges arranged in a corridor order.

The internal diameter of the channel is D = 0.018 m, the wall thickness is δ = 0.002 m, the length is L = 1.6m. The relative pitch S between the axes of the concavities is S / h = 10 (the h-radius of the concavities), the concavity setting angle φ = 120 °. The walls of the channel were modeled as aluminum and heated to a temperature of t_{wall}=105°C. At the entrance of the channel supplied working fluid - water, with a temperature t_{inlet}= 20°C.

In this work using a model of a periodically pulsating internal fluid flow (1) with a sinusoidal type speed pulses (Fig. 1.):

$$V(t) = 0.4\,(1 + A \sin(2\pi f t))\ \text{m/s}, \qquad (1)$$

Here t is time, V(t) is a flow rate, A = 1 is an amplitude of the pulsations. The time-averaged flow rate for the all cases are the same and equal V_0 = 0,4 m/s.

For the velocity V_0 = 0,4 m/s the average Reynolds number is $Re_0 = V_0D/\nu$ = 7157, where $\nu = 1{,}006 \cdot 10^{-6}$ m^2/s is the kinematic coefficient of water viscosity at t_{inlet}= 20°C.

With a changing in the average Reynolds number, the average velocities changing accordingly. The instantaneous values of the Reynolds numbers $Re_t = V(_t)D/\nu$ depend on time and for the case (1) are described by the equitation

In the calculations, the range of the flow pulsation frequency 0 ≤ f <130 Hz was investigated.

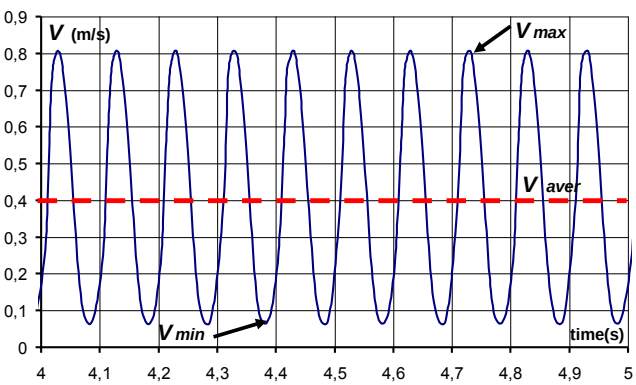

Fig.1. *Flow velocity profile: dashed line - average speed; smooth line - speed, determined by equitation (1).*

For mathematical modeling of the medium's motion and heat transferring, the unsteady Navier-Stokes equations are used. The resulting open-loop system of equations is closed with using of the additional equations for the kinetic energy of turbulence k and dissipation of the energy of turbulence ε in accordance to the known k - ε model of turbulence [11].

For the numerical solution of the Navier-Stokes system of equations in Flow Simulation software using the finite volume method with an adaptive rectangular grid [11]. In the calculation process the initial grid of finite volumes in the computational area is crushed automatically or according to a given law in the areas of assumed large gradients of each of the dependent variables or in areas of significant change in the curvature of the solid surface. For a satisfactory accuracy of the results of the solution in this work required about 1000000 - 1200000 liquid and solid elements.

Note that, in accordance to the calculation methodology, any stationary problem is initially solved as non-stationary. The solution is considered to be found after its establishment in time.

The results of numerical calculations, generalizing a series of computer experiments, were processed in the dimensionless Reynolds Re, Strouhal Sh, and Nu Nusselt criteria:

$$Re_0 = V_0D/\nu,\ \ Sh = f\,D/V_0,\ Nu = \alpha\,D/\lambda\,, \qquad (3)$$

where Sh – the dimensionless frequency of flow pulsations, α [B/(m^2K)] – the heat transfer coefficient, λ [B/(m K)] – the heat conduction coefficient of the liquid.

4. Results and discussion

The results showed that unlike to the stationary case with a unique dependence Nu = φ(Re_0) in a pulsating flow, the instantaneous values of the coefficient Nu(t) = φ(Re_t) changing with changing the instantaneous values of the Reynolds numbers Re_t (the Re_t value is determined by equitation (2)). Changes in the instant Reynolds numbers are shown in Fig. 2. In the stationary case with V_0 = 0,4 m/s, the Reynolds number is Re = 20000. For example, in a pulsating flow at a pulsation frequency of f=20Hz (Strouhal number Sh = 0.9) and an average speed of V_{aver}(t)=0,4 (m/s), the average value of the Reynolds number increases to Re≈27000, as well as has it's minimum Re≈50000, and the maximum Re≈47000 value.

As a result for the each value of Re_t corresponds to its own Nu value and is limited to its minimum Nu_{min} and Nu_{max} maximum values. This effect is due to the periodic change in the Reynolds number and the inertia of the processes during unsteady fluid flow in the channel.

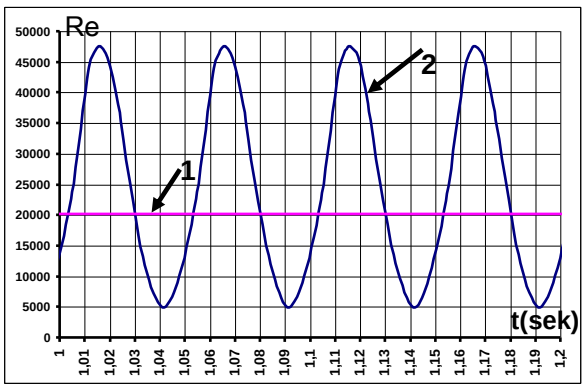

Fig. 2. *Changing of the instant Reynolds numbers. Line 1 - stationary flow V_0 = 0,4 m/s; line 2 - pulsating flow f = 20Hz (Sh = 0.9) V_{aver} (t) = 0.4 (m/s).*

For the dependence Nu = φ (Sh) can be selected conditionally three characteristic areas (Fig. 3.). In the first zone, 0 <Sh <2, the frequency of the flow velocity pulsations leads to the increasing in the average values of the Nusselt Nu_{ever} numbers in relation to Nu_0 for the stationary regime of the fluid flow.

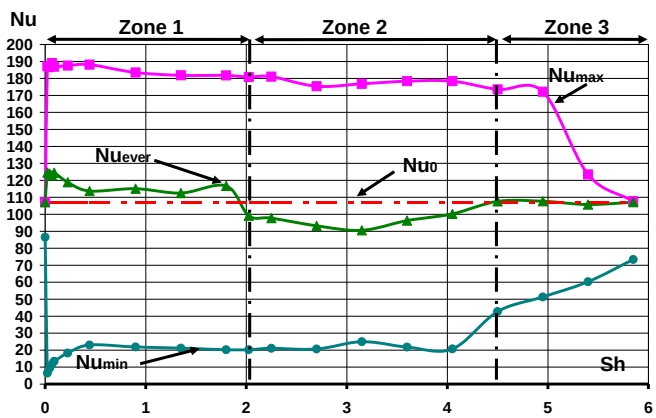

Fig.3. *The dependence of the Nusselt number on the dimensionless frequency of flow pulsations Nu = φ (Sh).*

In the second area 2 <Sh <4.3, the average values of the Nu_{ever} numbers become lower relative to Nu_0 by about 10-15%. In Fig. 2 can be noted that when the dimensionless Strouhal number Sh ≈ 2 is reached (zone 2), the heat exchanging getting worse. In the third zone, 4.3 <Sh <6, the average Nu_{ever} value in relation to Nu_0 stabilizes and the value of Nu remains almost unchanged and the flow pulsations have almost no effect on the heat transferring.

Fig. 4. shows visualization of a flow in a channel with a discrete roughness (longitudinal section), in the case of stationary flow of a fluid at average speed at the entrance to the channel V_{inlet} =0,4 m/s. The flow under consideration can be conditionally divided into the three areas: I – the outer boundary layer, II – the mixing region, and III – the return flow.

The flow picture can be presented as follows. The incident flow V at the exit from the concavity is turbulized, mixed with the medium in the concavity, and carries particles of the liquid from the mixing zone to the main flow. At the same time at an environ of the outlet edge the flow is splitting. One part of the flow (laminar sublayer) moves along the straight wall of the channel, the other part goes around the surface of the concavity and when it reaches the input edge of the concavity (inlet edge) it breaks down and forming a vortex.

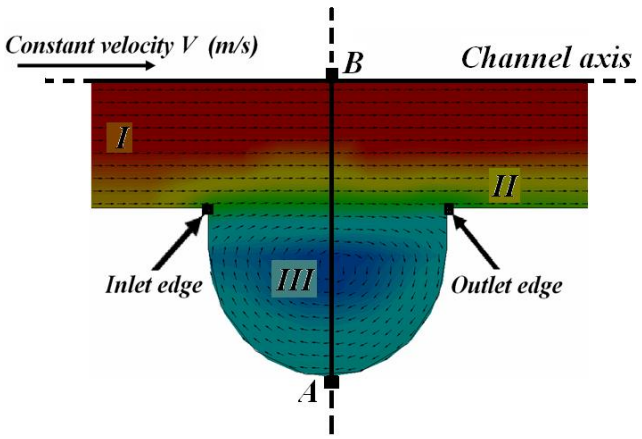

Fig.4. *The flow pattern with a stationary flow V_{inlet} =0,4 (m/s) concavities in the channel (longitudinal section).*

The Fig. 5. shows the temperature distribution on the transverse axis of the channel AB (r (mm)); the steady flow is V_{inlet} =0,4 m/s line 1 – is a smooth channel and line 2 – is a discretely rough channel.

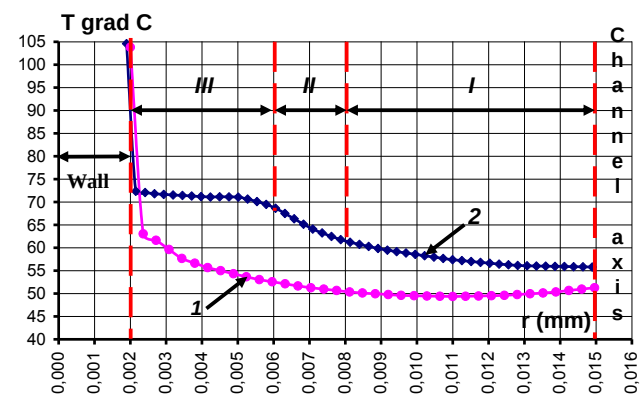

Fig.5. *Temperature distribution along the transverse axis of the channel AB.*

In comparing with the stationary motion in the pulsating mode, the flow patterns changing at time t(s).

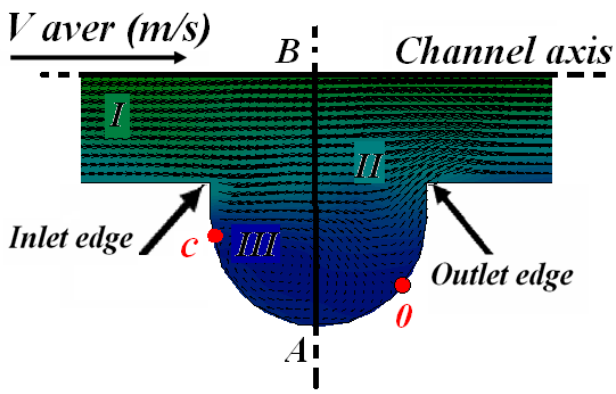

Fig.6. *The flow around the pulsating flow $V_{aver}(t)$ (m/s) concavity in the channel (longitudinal section) f = 20Hz (Sh = 0.9).*

Unlike to the stationary flow, in the pulsating mode at an average flow velocity of $V_{aver}(t)$ (equation (1)), the pulsating frequency f = 20Hz (Sh = 0.9) Fig. 6., the flow pattern are changing. Here, the inlet flow V_{aver} moves along a straight channel when the input edge of the concavity (inlet edge) is reached, the flow is splitting: one part of the flow moves towards the output edge (outlet edge), the other part towards the point ***0***, where it is turbulized and mixed. So unlike to the stationary mode, it shifts from the outlet edge (outlet edge) towards the axis AB by approximately 45 °. In the same place, at point 0, one more splitting of the flow occurs. One part of which (laminar sublayer) moves along the surface of the concavity towards the outlet edge (outlet edge) and then continues to move along the straight channel wall. The other part flow around the surface of the concavity and when it reaches point C, it breaks down and forming a vortex. At the same time unlike to the stationary flow, the center of the vortex that was on the axis AB, in the pulsating mode, the center of the vortex shifts towards the input edge by a distance approximately equal to half of the radius of the concavity.

When the maximum flow rate Fig.7. $V_{max}(t)$ is reached, the flow pattern is simplified, the flow moves along the straight channel wall, and when the input edge (inlet edge) is reached, part of the flow moves in a straight line to the output edge (outlet edge), and a part flow around the concavity and joins main flow around the exit edge. At the same time, no flow separation or vortex zones are observed in the concavity.

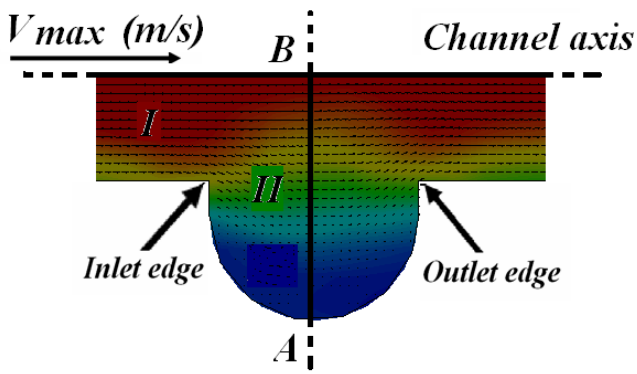

Fig.7. *The flow around the pulsating flow $V_{max}(t)$ (m/s) concavity in the channel (longitudinal section) f = 20Hz (Sh = 0.9).*

The complex flow pattern is observed when the minimum flow rate $V_{min}(t)$ is reached Fig.8.. Here the flow in the laminar sublayer changes it's direction to the opposite, in relation to the inlet flow and moves from the output edge (outlet edge) to the input edge (inlet edge). When reaching the entrance edge, the flow is splitting and part of it moving along the straight wall of the channel, and part

begins to move closer to the channel axis, where it merges with the main fluid flow, and thus forms a vortex zone III. The center of the vortex is located on the axis AB and at a distance approximately equal to half the radius of the smooth part of the channel.

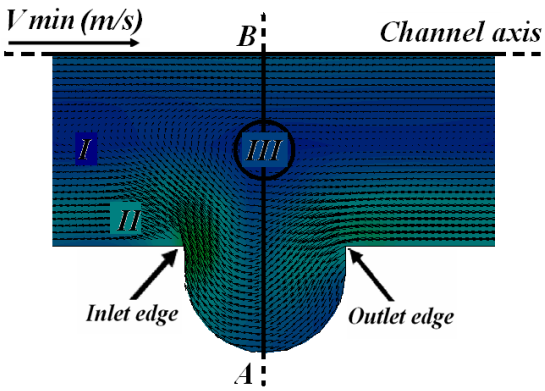

Fig.8. *The flow around the pulsating flow V_{min} (t) (m/s) concavity in the channel (longitudinal section) f = 20Hz (Sh = 0.9).*

So it can be assumed that the presence of vortex structures and return flow zones on the heat exchanging surface leads to the destruction of the boundary layer and, accordingly, intensifies the heat exchange processes. And the occurrence of such disturbing factors in the flow significantly affects both the hydrodynamics of the flow and the heat transferring.

5. Conclusion.

In this work was established that nonstationary processes can be accompanied by both an increase and a decrease in the intensity of heat transferring.

It is shown that this is due to the presence of vortex structures and backflow zones on the heat exchanging surface. Which lead to the destruction of the boundary layer and, as a consequence, lead to the intensification of heat exchanging processes.

It is revealed that the periodic pulsations of the flow velocity of fluid in discretely rough channels have a significant effect on the heat transferring coefficient Nu.

Unlike to the stationary case, in a pulsating flow, the instantaneous values of the coefficient Nu changing as the instantaneous values of the Reynolds numbers Ret.

The presence of the three characteristic zones of dependence of the Nusselt number Nu on the dimensionless Strouhal number Sh Nu = φ (Sh) is established. In the first zone (0 <Sh <2), the pulsations of the fluid flow in the channels improve the average intensity of the heat exchange. In the second zone (2 <Sh <4.3), the average intensity of the heat exchange is accompanied by a decreasing.

In the third zone (4.3 <Sh <6), the flow pulsations have practically no effect on the average value of the heat exchanging, and the average value of the Nusselt number becomes approximately the same as for the stationary flow.

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