# Modelling of hydrodynamic processes inside coaxial channels of regular packing of cooling tower

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*Abstract – The report is devoted to the analysis of physical processes associated with the motion of two-phase (fluid-gas) media inside the regular packing of cooling towers. Axisymmetric laminar flow inside the system of vertical coaxial infiniteness channels is considered. The mathematical formulation of the problem reduces to a boundary-value problem with the corresponding boundary conditions. The obtained analytical solution of the problem allowed carrying out a qualitative analysis of the flooding process in regular packing of cooling towers. It was shown that the flooding process begins on the inner surfaces of channels that located closer to the axis of the flow in regular packing of cooling tower.*

Keywords – Two-phase flow, boundary-value problem, coaxial channels, flooding, regular packing, viscous flow.

## I. Introduction

The extremely fast development of scientific and technical thought stimulates today many researches in different fields of classical physics. There are an enrichment of different sections of knowledge with new ideas and methods of research, and the formation of a large number of scientific problems, the solution of which requires practice today. A deep understanding of the physical features of transport processes in continuous media opens new opportunities for researchers and developers of various specialties in the design of new cooling systems, the creation of effective cooling towers in heat power engineering, chemical and pharmacological industries and other innovative technologies. Recently, this problem remains the actual one.

Complex physical processes occur in the gas flow inside the regular packing of cooling tower. Various phase changes lead to the appearance of a fluid film on the internal surfaces of the channels. The dynamics of this fluid can have a significant effect on the efficiency of heat exchanger apparatus, and in some cases can leads even to uncontrolled regimes. Such regimes in two-phase flows are called in the technical literature as critical regimes.

Theoretical analysis of the flooding process is associated with appearance of Kelvin-Helmholtz instability in continuous media under the action of forces of various physical natures.

Phenomenological study of the flooding regime [1] is always limited by the parameters of regular packing of cooling tower. Analytical investigation [2-3] are based on the representation of a fluid film as a smooth surface, or a wave surface. The latter option is semi-empirical. An analytical solution to this problem requires a sequence of experimental dependencies. Often this aspect in research limits its applying in the design of regular packing of cooling tower for various purposes and geometry.

The parameters of a smooth fluid film are calculated on the assumption that the viscous fluid flow is stationary, and its motion is averaged over the cross section. In other words, many researchers assume that the velocity of motion of a fluid film depends on the balance of pressure force, frictional force and gravity force. In fact, this problem is reduced to determine the value of these three forces, which depend on velocities of gas and fluid phase components.

Both experimental studies, and many observations show that the fluid film, despite a small relative thickness, is a continue environment that has own velocity distribution. A viscous fluid near a solid surface does not move, while the fluid-gas interface can have a nonzero velocity. Consequently, the velocity distribution inside the fluid film is important for the formation process of the flooding regime in the regular packing of cooling tower.

The main purpose of this research is determination of a quantitative relationship between the average velocities of the gas flow inside the coaxial channel system at critical regime, which leads to a flooding process in regular packing of cooling tower.

## II. Mathematical model

Consider the stationary axysymmetric laminar motion of a two-phase flow (fluid-gas) inside infinite straight coaxial channels with a circular cross-section ($R_1$ is the radius of the inner channel, $R_2$ is the radius of the outer channel) located vertically (fig. 1). Let the gas with density $\rho_1$ and coefficient of dynamic viscosity $\mu_1$ fill the middle part of the system ($R_1 + h \leq r \leq R_2 - h$), while a fluid with density $\rho_2$ ($\rho_2 >> \rho_1$) and coefficient of dynamic viscosity $\mu_2$ placed near hard surfaces ($R_1 \leq r \leq R_1 + h$, and $R_2 - h \leq r \leq R_2$), where $h$ is the thickness of the fluid layer. A pressure gradient $dp/dz$ = const is formed in the channel for driving the gas from the bottom upwards.

It is necessary to determine the distribution of the longitudinal velocity components $U_2(r)$ of the gas and $U_1(r)$, $U_3(r)$ of the fluid in a cross section of the coaxial channels.
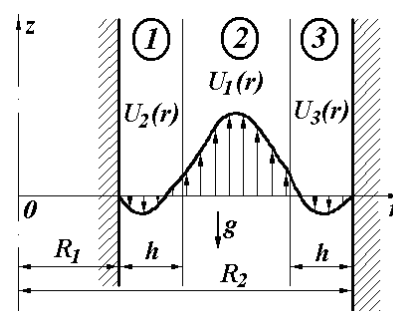


Fig.1. Geometry of the problem

The basic equations describing the motion of media are the Navier-Stokes equation, which for the axisymmetric

case in a cylindrical coordinate system $(r, z)$ coincided with the axis of the channel, reduce to a system of ordinary differential equations, as following [4]

$$\begin{cases} \dfrac{m_1}{r}\dfrac{d}{dr}\left(r\dfrac{dU_1}{dr}\right)=\dfrac{dp}{dz}, & R_1+h\le r\le R_2-h \\[2mm] \dfrac{m_2}{r}\dfrac{d}{dr}\left(r\dfrac{dU_2}{dr}\right)=r_2 g+\dfrac{dp}{dz}, & 0\le r\le R_1+h \\[2mm] \dfrac{m_2}{r}\dfrac{d}{dr}\left(r\dfrac{dU_3}{dr}\right)=r_2 g+\dfrac{dp}{dz}, & R_2-h\le r\le R_2 \end{cases} \quad (1)$$

where $U_1(r)$, $U_2(r)$ and $U_3(r)$ are longitudinal components of the velocity of gas and liquid in the corresponding parts of the channel, $dp/dz$ is a pressure gradient formed in the channel, which establishes movement within the channel, and $g$ is acceleration of gravity.

Considered boundary value problem (1) contains the following boundary conditions

$$U_2(R_1)=0, \qquad U_2(R_1+h)=U_1(R_1+h),$$

$$m_1\dfrac{dU_1}{dr}\bigg|_{r=R_1+h}=m_2\dfrac{dU_2}{dr}\bigg|_{r=R_1+h}, \qquad (2)$$

$$U_1(R_2-h)=U_3(R_2-h), \quad U_3(R_2)=0,$$

$$m_1\dfrac{dU_1}{dr}\bigg|_{r=R_2-h}=m_2\dfrac{dU_3}{dr}\bigg|_{r=R_2-h}.$$

The first and the last boundary conditions in eq.(2) are no-slip condition for a viscous liquid at a solid surface. The second and fourth conditions in eq.(2) are the conjugation conditions for media with respect to velocity, while the third and fifth expressions are the conjugation conditions in respect to tangential stress.

The mathematical problem (1) together with boundary conditions (2) has the analytic solution $U_1(r)$, $U_2(r)$ and $U_3(r)$, which is presented in the report. This solution allows us to obtain analytical expressions for the volume capacity rate of gas $Q_2$ and fluids $Q_1$ and $Q_3$ through the cross section of the channel. In this case it is necessary to calculate the following integrals

$$Q_1=2p\int_{R_1+h}^{R_2-h} U_1(r)\cdot r\,dr,$$

$$Q_2=2p\int_{R}^{R_1+h} U_2(r)\cdot r\,dr, \qquad (3)$$

$$Q_3=2p\int_{R_2-h}^{R_2} U_3(r)\cdot r\,dr.$$

On the basis of [5, 6] was taken that at the flooding process the volume capacity rate of fluid leads to zero, so $Q_{1m}=0$ or $Q_{3m}=0$. This condition allows us to determine the values of the pressure gradients $(dp/dz)_{1m}$ or $(dp/dz)_{3m}$, which have to be applied to the channel to achieve the

flooding regime. Analogue of obtained results allows to conclude that the values of the pressure gradients for the flood regime depend both on the geometry of the channel (the ratio between $R_1$ and $R_2$), but also on the thickness $h$ of the films at inner and outer surfaces of the channel.

These pressure gradient values, $(dp/dz)_{1m}$ or $(dp/dz)_{3m}$, are used to determine the gas velocity profile $U_2(r)$ in the middle part of the channel.

## III. Numerical analyse

As an example, we consider the motion of a two-phase medium (water-air) inside a coaxial chanel ($R_1 = 5.0\cdot10^{-3}m$, $R_2 = 10\cdot10^{-3}m$) system with a thin fluid film $h = 0.5\cdot10^{-3}m$.

Fig.2 shows the gas and fluid velocity profiles that are formed inside the system of coaxial channels at different modes: the counter-flow regime (the most of the gas and fluid move in the opposite directions), the loading regime (fluid and gas velocities at the interface is zero) and flooding regime (volume capacity rate of the fluid at the cross section of the channel is zero). It is shown that the velocity profiles have a shape close to the parabolic shape for all regimes. It indicates that the laminar gas flow in the middle part of the channel is achieved. It is interesting to note that gas and velocity near interface moves in the same direction (downwards) in the counter-flow regime (Fig. 3).

Analysis of the curves in fig.2 and fig.3 shows that the local velocity of the film at the interface between media 2 and 3 is lower in comparison with the corresponding velocity at the interfaces between media 1 and 2 for different values of the average gas velocity in the middle part of the coaxial channels. In other words, the flooding process begins on the inner surface of the channel (the interface between media 1 and 2) for different values of radii $R_1$ and $R_2$.
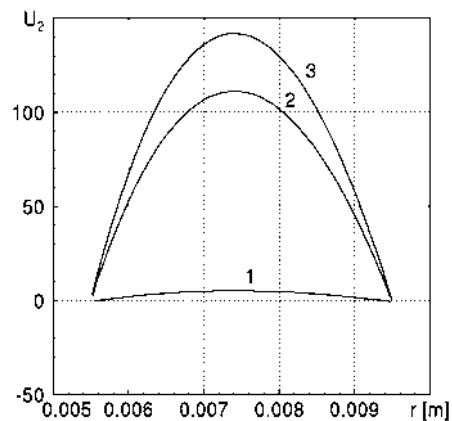
Fig.2. Distribution of velocity in the gas for: 1 – counter-flow regime, 2 – loading regime, 3 – flooding regime
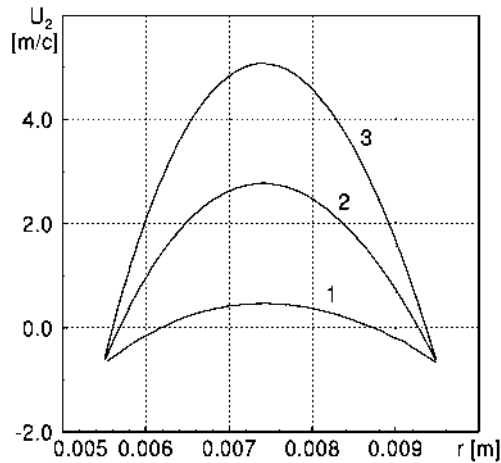
Fig.3. Distribution of velocity in the gas for counter-flow regime for different velocity profiles in the gas: 1 – $dp/dz$ = -10 $Pa$, 2 – $dp/dz$ = -30 $Pa$, 3 – $dp/dz$ = -50 $Pa$

Figure 4 illustrates the dependence of the average gas velocity inside the channel for the flooding regime on the values of the channel radii $R_1$ at constant film thicknesses $h$ and the width of gas channel $H = R_2 - R_1$. We can see that the velocities remain approximately at the same level over a wide range of values of the internal radius of the channel. However, they display different dependencies. On the one hand, increasing the radius $R_1$ of a smaller channel leads to increasing values of the gas velocities, at which the flooding regime occurs. On the other side of the channel, an inverse dependence is observed. Increasing the radius $R_1$ leads to a decrease in values of the average gas velocity. A comparison of this figures shows that the gas velocity, at which the flooding regime takes place, on the inner surface of coaxial channel system is always smaller than the corresponding velocity for the outer surface of he channel. In other words, the flooding process always begins on surfaces closer to the axis of the flow.

The dependence of the average gas velocity needed for forming the flooding regime on the fluid film thickness $h$ at constant values of the internal radius $R_1 = 5.0 \cdot 10^{-3}m$ of the channel and the width $H = 5 \cdot 10^{-3}m$ of the gas channel is shown in Fig.5. Increasing the thickness of the film leads to an increase in the average gas velocity. This trend is preserved up to values $R_1 \approx 0.9 \cdot 10^{-3}$ $m$. There are extreme values of the velocity. Then, increasing in the film thickness leads to a decrease in the corresponding averaged values of the gas velocity. This tendency is typical [6] and corresponds to the physical features of the flooding process in regular packing of cooling tower systems. Some detail physical processes in two-phase flows in infiniteness circular channels with vertical orientation we can find in monograph [5].

Analysis of the analytical dependencies and numerical data shows that the average gas velocity, at which the flooding regime is formed, is always large for the outer surfaces of the coaxial channel system as compared to the corresponding values for the internal surfaces. Moreover,

these values actually depends on the thickness of the film, which arises on the solid surfaces of regular packing of cooling tower. It is shown that an increase in the width of the gas channel leads to an increase in the values of the average gas velocity, at which the flooding regime on the inner surface of the coaxial channel system begins to form.
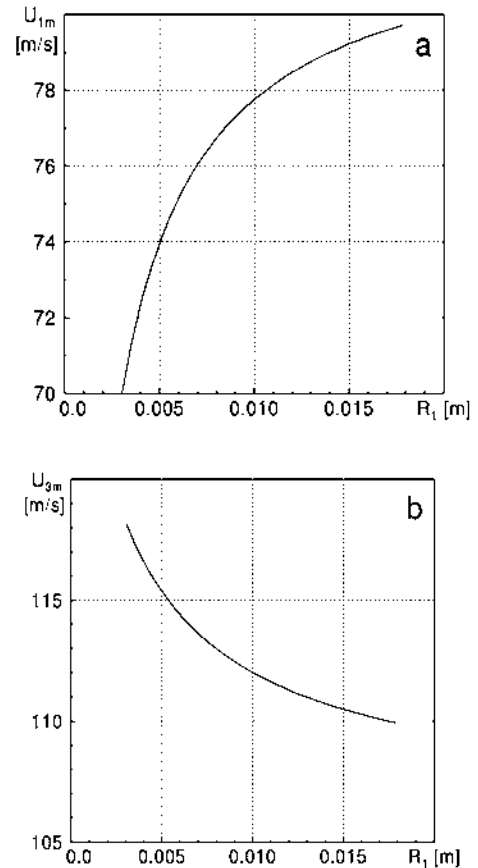


Fig.4. Dependence of overate gas velocity at flooding regime on radius of the channel for: a – internal surface, b – outer surface of the channel system



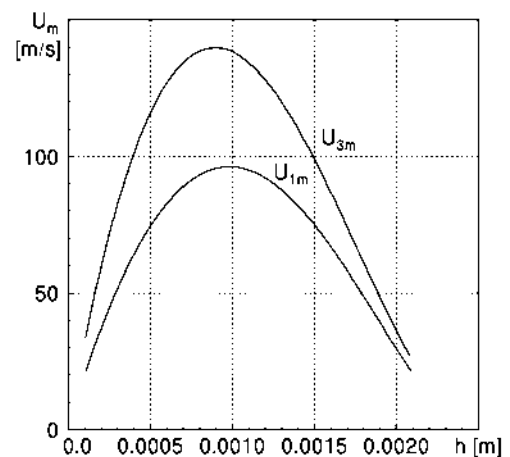Fig.5. Dependence of overate gas velocity at flooding regime on thickness of the fluid film for internal and external surfaces of coaxial channel system

## Conclusion

The problem of motion of a two-phase laminar flow (gas-fluid) inside an infinite rectilinear system of coaxial channels placed vertically is considered. The mathematical formulation of the problem reduces to the solution of axisymmetric Navier-Stokes equations in a cylindrical coordinate system together with boundary conditions at interface surfaces.

This problem has an analytical solution that has allowed to establish quantitative regularities of the flooding process in dependence on the physical properties of gas and fluid, the geometric parameters of the channel and the thickness of the fluid film formed on solid surfaces.

An analysis of achieved results shows that the flooding process begins at lower averaged along cross-section gas velocities for narrow channels. This process begins on the inner surfaces of the channel, located closer to the axis of the flow. Increasing the average gas velocity in the middle part of the channel system leads to the appearance of the flooding regime on the outer surfaces of the channel. This process can occur in a narrow range of gas velocities.

It is shown that the flooding process appears in narrow channels at lower averaged velocities. Moreover, this process depends on the thickness of the fluid film. The profile of the longitudinal component of the fluid velocity inside the films can vary with sufficiently large gradient forming a viscous friction force commeasurable with the gravity force.

The quantitative particularities of the influence of dynamic parameters of a continuous medium and flow geometry on the flooding process in contact devices containing a system of coaxial channels placed vertically. The obtained data can provide a certain support to researchers, designers and developers of regular packing for various purposes and different geometry.

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