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Investigation of the motion and heat transfer of water droplets in the swirling air flow in weightlessness

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Abstract. The motion and heat transfer of water droplets with a swirling air flow is investigated. Flow was considered in a cylindrical chamber in the absence of gravity. We created a mathematical model of this problem and made appropriate calculations. The features of the air flow at a tangential feeding it into the chamber, and the motion of the drops, their thermal behaviour are founded. We presented the recommendations for the rational choice of parameters of the apparatus and rational operation regime.

1. Introduction
As a result of the contact of air and other gaseous media with a liquid, this is usually heavily dispersed, located in the gas solid particles deposited on the interface. Combined cycle gas contaminants absorbed by liquid. In the presence of the temperature difference between these mediums the heat transfer takes place. Also, evaporation or condensation of liquid on its interfacial surface are possible.

In one form or another, these processes are implemented in wet scrubbers [1], to some extent, in the cooling towers [2-4]. In the absence of gravity cleaning processes, heat and mass transfer can be implemented in the working chamber of apparatus. In this chamber, tangentially supplied air with impurities irrigated with water. It should be noted that the swirling vortex flow are widely used in engineering: vortex separators, cyclones, precipitators, dryers, cyclic furnaces, burners, plasma devices [5-7].

2. Results of numerical simulations and analytical estimates
Issues of mathematical modeling of isothermal and non-isothermal swirling flows devoted to work [5], [8-9], numerous articles. In this paper, modeling of non-isothermal flows of two-phase medium is carried out using a complete system of equations of turbulent motion, including a standard two-parameter $k-\varepsilon$ turbulence model, initial and boundary conditions. In describing the motion of water droplets applied Lagrange continuum approach. Integration of the corresponding system of equations is carried out numerically by finite volume method.
The computational domain consists of a cylindrical chamber with a pipe. Total height of the chamber 0.9 m, the diameter of the inlet pipe is 0.07 m (figure 1). The air velocity in the inlet pipe is taken 25 m/s, the temperature 303 K. Water-spraying device is located in the chamber at a distance 0.135 m from the lid. The drops are injected against the flow of air at a rate 1.0 m/s, water temperature 283 K.

We found that due to the tangential supply of air into the chamber it acquires rotary motion. The maximum rate is achieved in the region where the air from the nozzle accumulates on the concave wall of the chamber (figure 2). Further, the stream of air flows over the surface and twists. The minimum value of the circumferential velocity component $v_z$ takes the central part of the chamber, and the maximum near the concave surface.

Changes in the velocity magnitude in the cross sections of the chamber $x = 0.2$ m, 0.55 m, 0.85 m illustrated on figure 3. It is evident that the distance from the entrance to the change velocity magnitude in the radial direction becomes more uniform.

We shown that in the central portion of the chamber drops fairly long time moving against the air flow (figure 4). While the droplets, which was ejected on the periphery, almost immediately addicted to the carrier medium. Also, they are changes its original direction of movement. Some of these droplets nailed to the walls of the chamber. From the results of calculations that the average air
temperature at the exit of the chamber is about 298 K, wherein the periphery is slightly lower than in the central portion of the chamber.

We made further simplifications in order to obtain engineering dependencies for evaluating the main indicators of this apparatus. At the front of the chamber the flow of air and the movement of water droplets is not significantly regular, so they are not considered. We suppose that the working environment (air) - ideal fluid. At the rotational-translational motion in the central part the vortex core is formed. The flow considered a potential outside core on the periphery [5]. However in contrast to [5], where the district \( v_\phi \) and longitudinal \( v_z \) component of the velocity vector of the air have angular points, approximation suggested some excluded them:

\[
\begin{align*}
  v_\phi &= \begin{cases} 
    \omega r \left( 3 - \frac{2r}{r_1} \right), & 0 \leq r \leq r_1; \\
    \omega r_1^2 / r, & r_1 \leq r \leq a.
  \end{cases} \\
  v_z &= \begin{cases} 
    v_0 \left( 1 - \left( \frac{r-r_1}{r_1} \right)^2 \right), & 0 \leq r \leq r_1; \\
    v_0, & r_1 \leq r \leq a.
  \end{cases}
\end{align*}
\]
Where \( r \) – the coordinate in the transverse direction of the cylindrical coordinate system \((z,r,\varphi)\), \( r_1 \) – the radius of the surface section of the vortex and potential flows of air,

\[
r_1 = 0.5a \sqrt{3(p_a - p_0 - 0.5\rho_1 v_0^2) / (\rho_1 \omega^2 a^2)};
\]

\( a_0 \), \( a \) – the radius of the central tube and the cylindrical wall of the chamber; \( \omega \) – the angular velocity of rotation of the air, \( v_0 \) – longitudinal velocity on the periphery of the flow associated with the average estimated velocity \( w_r \) by ratio

\[
v_0 = w_r a^2 / \left( a^2 + r_1^2 - r_2^2 / 6 \right);
\]

\( \rho_1 \) – the density of air; \( p_a, p_0 \) – the pressure at infinity and the center of the vortex (at the central part of the chamber). According to the law of conservation of momentum \( \omega \) determined from the equation

\[
\omega = u_1 \sqrt{2\pi w_r r_1^2 \left( a - \frac{or_2^2}{\lambda_1} \right)},
\]

where \( u_1 \) – the average speed in the inlet pipe of the working chamber, \( G_1 \) – the air flow rate,

\( \chi_1 = \sqrt{3(p_a - p_0 - 0.5\rho_1 w_r^2)} / \rho_1 \).

As a result of integrating of the drop motion equations wherein the drag force is determined by the Stokes formula, we found that the longitudinal speed \( u_p \) close to the air velocity \( v_r \), the drop velocity \( v_p \) in the transverse direction along the axis \( r \), described by the relation:

\[
v_p = \left[ v_{p0} + (1 + \chi^2) \bar{v}_{p0} \right] \left[ R_p \left( R_p^2 - 2(R_p^2 / 1 + \chi^2) + 1 / R_p \right) \right]^{1/2}.
\]

Where \( \tau \) – the time, \( r_0, v_{p0} \) – the initial coordinates, the drop velocity; \( \bar{v}_{p0} \) – averaged over the cross section of the circumferential speed of the air, \( \chi = (w_{p0} - \bar{v}_{p0}) / \bar{v}_{p0} \), \( w_{p0} \) – the initial circumferential velocity of the drop, \( R_p = 6\pi r_p m_p / m_p \); \( r_p, m_p \) – the radius, mass of the drop. The drop peripheral velocity \( w_p = (w_{p0} - v_{p0}) \exp(-R_p R + v_{p0}) \).

Considering further drop of thermally thin body, its temperature determine

\[
\theta_p = \tilde{t}_1 + (\theta_{p0} - \tilde{t}_1) \exp(-\tau K_a) - \tilde{t}_1.
\]

Where \( \theta_{p0} \) – the initial volume average temperature of the drop, \( \tilde{t}_1 \) – the average temperature in the considered part of the chamber,

\[
\tilde{t}_1 = \frac{2c_1 G_{1m} \tilde{t}_{11} + c_2 G_{2m} \theta_{p0} (1 - \exp(-\tau K_a))}{2c_1 G_{1m} + c_2 G_{2m} (1 - \exp(-\tau K_a))},
\]

\( \tilde{t}_{11} \) – the average air temperature at the inlet of the selected portion of the chamber; \( G_{1m}, G_{2m} \) – the mass flow of the air, water in the chamber respectively; \( c_1, c_2 \) – the specific heat capacity of air, water; \( K_a = \alpha_s s_p / (m_p c_p) \), \( s_p \) – the drop surface area.

At the initial air temperature \( \tilde{t}_{11}=303 \) K, water \( \theta_{p0}=283 \) K, the flow rate \( G_{1m}=0.1 \) kg/sec, \( G_{2m}=0.04 \) kg/sec, \( c_1 = 1.0 \cdot 10^3 \) J/(kg·°C), \( c_2 = 4.2 \cdot 10^3 \) J/(kg·°C) and the flight time of the drop \( \tau_f = 1.5 \) sec find \( \tilde{t}_1=301 \) K. Consequently, the output from the chamber average temperature \( \tilde{t}_{12}=299 \) K, the water temperature is about 285 K.

3. Conclusions
Thus, on the basis of the results we made the following conclusions.

1. Initially, there is substantially unequal air flow. Drops motion away from the inlet stabilized fairly quickly. This fact is the basis to apply the analytical methods.
2. To reduce the proportion of the drops deposited on the walls, better to make the chamber as a conical shape. Furthermore, it can be achieved by increasing the pipe diameter.
3. Generation of acoustic waves in the chamber provides an intensification of heat and mass transfer. Also, it will allow to reduce the temperature of the air.

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References
[9] Tarasevich S E, Fedyaev V L, Yakovlev A B and Morenko I V 2012 Int. Conf. on Nanochannels, Microchannels and Minichannels HT 2 109