Calculation of the film flowing over horizontal tube surface

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Abstract. Hydrodynamic processes taking place during the motion of liquid droplets and the
formation of a liquid film flowing over surface of a horizontal tube are considered. Mathematical modelling of motion of two-phase medium is based on the Lagrangian approach. The results of numerical calculations of the liquid film thickness over surface of the tube are presented.

1. Introduction
The flow of liquid films over three-dimensional surfaces is presented in nature and some technological processes. Research of the deposition process of liquid functional coatings is relevant in medicine, engineering, energy, chemical industry. The deposition of metal, dielectric and semiconductor coatings is used in the manufacture of integrated circuits. Ceramic coatings protect the details and mechanisms of corrosion, oxidation and wear, is increased resource cutting instruments. The use of modern computer technology and mathematical modelling allows you to select technological equipment and its modes of operation rationally and scientifically.

The regime of the film flow over surface depends on the Reynolds number, the physical properties of the fluid, surface roughness and other factors. At low Reynolds numbers the film flows over the smooth surface in the laminar regime, the film surface is smooth, no waves [1]. When the Reynolds number increases the gravitational waves are formed on the film surface. The ripple, short capillary waves are observed on the surface of the film in other cases. At high velocity of liquid film the flow becomes turbulent. Furthermore, thin films are often is torn, the dry regions are formed [2]. The droplet flow observed in the case of low liquid flow rates. The transverse instability of the contact line leads to separation of wet and dry regions of the flow [3].

In this paper the problems of directed motion of liquid droplets from the spray device, the subsequent formation of a thin liquid film and falling film over horizontal surface of the tube are considered. \( D = 0.1 \text{ m} \) is diameter tube. The part of the tube length \( L = 0.1 \text{ m} \) is considered. The axis \( Ox_3 \) of the Cartesian coordinate system \( x_1, x_2, x_3 \) is parallel to the axis of the tube (figure 1). The spray device is located on top at a distance 0.1 m from the tube.

It should be noted that the liquid atomization process on the cylindrical surface of the body includes a large number of interconnected physical processes: the formation of droplets, the movement of droplets in a gaseous environment, interaction droplets with the wall or the liquid film, the flow of thin liquid film, spraying, condensation, evaporation of the liquid and others.
2. Governing equations
Taking into account all factors fully at mathematical modeling is very difficult, therefore, makes a number of assumptions. The droplets have a spherical shape, the same diameter $d_p$, the drop rotation, the split, the merge, the evaporation, the condensation is not considered. The investigated processes are isothermal. It is believed that the gas velocity is zero.

General equations are written for the problems of calculating the trajectories of the droplets and the gravitational falling thin liquid film.

![Figure 1. Sketch of computational domain.](image)

The trajectory of the droplets is described by equations

$$\frac{dx_i}{dt} = v_{pi},$$

(1)

where $t$ is time; $v_{pi}$ is the the components of the velocity vector $\vec{v}_p$ of the drop. The motion equation of the drops is represented as

$$m_p \frac{d\vec{v}_p}{dt} = F_g + F_D,$$

(2)

where $m_p = (1/6) \rho_p \pi d_p^3$ is the mass, $\rho_p$ is the drop density.

In equation (2) takes into account gravity and buoyancy

$$F_g = \frac{\pi}{6} d_p^3 (\rho_p - \rho) \vec{g},$$

and the drag force acting on the droplet from the gas medium

$$F_D = \frac{3 \rho m_p}{4 \rho_p d_p} C_D (\vec{v} - \vec{v}_p) |\vec{v} - \vec{v}_p|,$$

where $\rho$, $\vec{v}$ is the density, the air velocity, $\vec{g}$ is the acceleration of gravity. The drag coefficient of drop $C_D$ depends on the Reynolds number of the drop $\text{Re}_p = \frac{\rho d_p |\vec{v}_p - \vec{v}|}{\mu}$:
The energy loss associated with overcoming the drag force at the laminar motion of a spherical body. In the case the turbulent flow past of the sphere the inertia forces are significant.

Numerical simulation of the flow of the liquid film is performed under the following assumptions. The laminar film flow is assumed. The velocity profile of the film in the normal direction is parabolic. The tangent component of the film velocity is significantly more than the normal component velocity. The normal component of the film velocity set to zero. The pressure is constant in the wall-normal direction.

Let \( \delta \) is the film thickness, \( \bar{u} = \frac{1}{\delta} \int_0^\delta \bar{u} \, d\delta \) is the mean tangential velocity of the film. The movement of the liquid film is described the continuity and momentum equations [4]

\[
\frac{\partial \rho \delta}{\partial t} + \nabla \cdot (\rho \delta \bar{u}) = S_{\text{imp}}, \tag{3}
\]

\[
\frac{\partial \rho \delta \bar{u}}{\partial t} + \nabla \cdot (\rho \delta \bar{u} \bar{u}) = -\sigma N \bar{u} + S_{\text{rho}}, \tag{4}
\]

where \( S_{\text{imp}} = \sum_j m_{p,j}^* \) is the mass source per unit wall area due to impingement, \( m_{p,j}^* \) is the mass flux of \( j \)-th impinging droplet.

In equation (4) the pressure \( p = p_{\text{imp}} + p_v + p_a + p_n \) is comprised the impingement pressure of droplet \( p_{\text{imp}} = \sum_j m_{p,j}(v_{p,j} \cdot \bar{n}) \), capillary effects \( p_a = -\sigma N \delta \), where \( \sigma = 0.072 \) N/m is the surface tension, the hydrostatic pressure \( p_a = -p_v \), the local gas medium pressure \( p_a \).

The term \( S_{\text{rho}} = S_{\text{rho, imp}} + \bar{\tau}_a + \bar{\tau}_v + \rho \bar{g}, \delta \bar{\tau}, \delta \bar{\tau}_\theta \) is comprised the momentum source per unit wall area due to impingement droplet \( S_{\text{rho, imp}} = \sum_j m_{p,j} \bar{v}_{p,t,j} \), the viscous shear stresses on the film surface \( \bar{\tau}_a \), the friction force \( \bar{\tau}_v = -\mu \bar{3} \bar{u} \delta \), the gravity force \( \rho \bar{g}, \delta \) \( \bar{g} \), is the gravity components tangential to the wall, the stress related to contact-angle force \( \bar{\tau}_\theta \).

The computation domain is subdivided using tools blockmesh into a nite number of control volume cells over which the governing equations are integrated. The numerical solutions of problem (1)–(4) are implemented in OpenFOAM licensed GNU GPL. Impose restrictions on Courant number \( C_0 \leq 0.3 \).

3. Calculation results

In the numerical experiments the following input parameters are given: the density of gas \( \rho_{g} = 1.2 \) kg/m\(^3\), the dynamic viscosity coefficient of gas \( \mu_{g} = 1.79 \) kg/(m·c), the density of liquid \( \rho_{l} = 10^3 \) kg/m\(^3\), the dynamic viscosity coefficient of liquid \( \mu_{l} = 10^{-3} \) kg/(m·c), droplet diameter \( d_{p} = 10^{-3} \div 5 \cdot 10^{-3} \) m, the drop velocity vector at the outlet from the spray device is directed
downwards $v^0_{p1} = 0 \text{ m/c}$, $v^0_{p2} = -0.5 \text{ m/c}$, $v^0_{p3} = 0 \text{ m/c}$. The liquid spraying begins at time $t = 0 \text{ c}$ and ends at time $t = 0.3 \text{ c}$. The mass flow rate is $0.023 \text{ kg/c}$.

The hydrodynamic regime of film motion is determined by the Reynolds number $Re = \frac{4 \Gamma}{\mu}$, $\Gamma$ is the flow rate. The Reynolds number of the film $Re = 460$, which corresponds to the laminar flow regime with a wavy air-fluid interface according to the given classification [1].

The calculations show that on the surface of the thin liquid film the waves observed when the film flowing under the gravity force over surface of the horizontal tube. The wave motion is due to the perturbations. These perturbations occur at the interaction of the falling liquid droplets with the thin film surface and the effect of surface tension forces. The results of numerical calculations of the film thickness are presented on figure 2.

| Figure 2. The thickness of the liquid film over tube surface at different times: 1 – $t = 0.13 \text{ c}$, 2 – $t = 0.18 \text{ c}$, 3 – $t = 0.26 \text{ c}$. |

It is shown that the film thickness $\delta$ less than $8 \cdot 10^{-4} \text{ m}$. At time $t = 0.13 \text{ c}$ the maximum value of the film thickness is achieved in the area of the tube surface $\theta = 130^\circ \pm 140^\circ$. The angle $\theta$ measured from the top of the tube. At times $t = 0.18 \text{ c}$, $0.26 \text{ c}$ the film thickness $\delta$ is not constant on the tube wall (curves 2, 3). The values of film velocity less than the velocity of drops at the outlet of the spray device $|v^0_p|$.

4. Conclusions
In conclusion, we note that for the given parameters of the spray device the thin liquid film is not completely covered the surface of horizontal tube. On the moving front of the liquid film the transverse instability of the contact line leads to the formation the rivulets.

References
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