Computer simulation of vortex flows near the condensation surface in the Laval-liked nozzle form vapour channel of short low temperature heat pipes at high heat loads

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Abstract. The results of the computer simulation of vortex formation near the condensation surface in the Laval-liked vapour channel of short low temperature heat pipes (HP’s) at high heat loads are presented. For the first time it was found that the vapour vortex of moist compressible vapour flow near the condensation surface inside the vapour channel of short HP’s changes its rotational motion direction, depending on the thermal load magnitude on the HP’s evaporator. With low thermal loads, the rotational motion direction of the vapour vortex due to the Coanda effect and sticking moving vapour jets to the walls of the channel occurs from the periphery to the center of the vapour channel. While the thermal load increasing, the direction of rotation of the vapour vortex changes to the opposite, from the center to the periphery. The thickness of the liquid condensate film located under the vortex also depends on the magnitude of the thermal load and the direction of the vortex rotation. The numerical calculation of the condensate film thickness of working fluid were compared with experimental values depending on the thermal load on the HP’s evaporator and obtained by capacitive sensors.

1. Introduction
Intensive development and implementation of short low-temperature range HP’s with increased heat transfer characteristics raise problems of detailed research of internal flow and condensation processes in vapour channels. In the case when the vapour channel is made in the form of the Laval-liked nozzle, and surrounded by the capillary-porous insert along the full length of the short HP’s, leads to increase the velocity and frequency of pulsations of moist vapor flow [1-3], heat transfer coefficient and condensation process intensity in compared with the HP’s with standard cylindrical vapour channel and equal overall dimensions [4-5], droplets centering in the vapour channel at high heat loads [6] and occurrence of the vapour vortex formations near the HP’s condensation surface [7-8]. Numerical simulation of the moist vapour flow inside the Laval-liked nozzle vapour channel of short HP’s unambiguously shows the occurrence of a vortex ring near the HP’s condensation surface, and this leads to velocity and pressure distribution change in the Laval-liked nozzle vapour channel and an increase in the HP’s heat transfer coefficient. This paper present the results of numerical simulation of the moist vapour flow in the vapour channel, similar to the Laval nozzle, the formation of vapour toroidal ring vortices near the HP’s condensation surface, and the influence of the vortices rotation direction on the liquid condensate film thickness (on the condensation surface), and comparison the calculated film thickness with the experimental results. Specially designed HP’s for measuring the condensate film thickness is shown in figure 1.

2. Materials and methods
The HP’s length is 100 mm, its external diameter is 20 mm, the max. diameter of the vapour nozzle in the convergent and divergent duct section is 16 mm, the critical nozzle throat diameter is 4 mm, the length of the nozzle convergent duct section is 13 mm, the total angle of the convergent section is 41°, the length of the nozzle divergent duct section is 81 mm, the total angle of the divergent section is 8.5°, and the length of the cylindrical section in the nozzle throat is 1 mm.

**Figure 1.** HP’s diagram: 1 – top cover; 2 – cylinder body of the HP’s; 3 – cone-shaped turbulator; 4 – capillary-porous insert; 5 – bottom cover; 6 – capillary injector channels, 7 – bottom flat capillary-porous insert-evaporator. There are capacitive sensors 8, 9, additionally installed inside the top cover [1-5] and shown in figure 2.

Porosity of the insert and evaporator is 72% and together they form one hydraulic system designed to deliver the working fluid to the evaporator when the HP’s is operating. Diethyl ether C₄H₁₀O is used as a working fluid, which has boiling temperature under atmospheric pressure of \( T_B = 308.65 \) K (35.5 °C), and dielectric constant \( \varepsilon = 4.3 \) (298K). The volume of the diethyl ether in the capillary-porous insert and the evaporator is not less than 18 cm³. The top cover 1 with installed capacitive sensors is shown in figure 2:

**Figure 2.** Layout of the installation of two capacitance sensors into the HP’s top lid: 1 – top lid of the HP made of stainless steel 1X18H9T; 2 – actual capacitance sensors that are laser welded to the lid 1 along their perimeter, herewith the polished gauging surface of sensors is flush-lined with the lid’s inner surface; 3 – glass insulators (glass-to-metal seals); 4 – gauging electrodes of both sensors; 5 – fastening nut of the HP filling unit that is welded to the inner surface of the lid 1; 6 – screw plug of the HP filling unit; 7 – capacitance sensor’s ground electrode; 8 – micro-thermistor that is a sensing element of thermistor CT3-19 and is laser welded to the tangential oriented end faces of the electrodes of one of the capacitance sensors. The micro-thermistor is 0.2 mm in diameter and is electrically insulated from the HP lid. The HP condensing surface of the top lid 1 and radially oriented end faces of the gauging electrodes of the capacitance sensor are also shown here.

Condensation zones of the HP’s with insulated thermocouples are set into the vortex continuous-flow calorimeter [4-5] with stabilized water flow. The HP’s evaporator, also equipped with thermocouples, is heated using a resistance heater, and the temperature is maintained at \( \delta T, K \) higher than the diethyl ether boiling temperature of \( T_B = 308.55 K \) (35.4°C) under atmospheric pressure. The heater temperature is stabilized and HP’s evaporators overheat value is set in the range of \( \delta T = T - T_B = 0 \div 20 K \).

### 3. Numerical results

Numerical simulations of the vortex flows inside a Laval-liked vapour channel of short HP’s have been performed in finite element modeling in CFD 10.0 code Fluent 6.3.26 under 2D, double precision axis-symmetric conditions. Navier-Stokes equations with measured boundary conditions were solved, i.e. using fixed temperature values of heat source and heat outlet. In the construction of the design model about 457233 finite elements were used, with increased meshing at injection capillary channels sections, nozzle throat section and turbulence element. Figures 3 and 4 show the calculation results of the vortex flow in the HP’s upper part, cooled by the flow calorimeter.
Figure 3. The occurrence of a vortex ring near the condensation surface inside of Laval-liked HP’s at low heat loads. Moving vapour jets due to the impact of the Coanda effect sticks to the HP’s walls and vortex ring formed from the periphery to the center of the vapour channel.

Figure 4. The occurrence of a vortex ring near the condensation surface inside of Laval-liked HP’s at higher values heat loads entering to the HP’s evaporator. In this case, the vortex ring formed from the center to the periphery of the vapour channel.

The numerical analysis of flow in the Laval-liked HP’s condensation zone shows that the vapour toroidal ring vortex structure has a spatial nature, at the same time the flow asymmetry becomes apparent being determined by non-linear friction against the underlying surface and the two-dimensional compressibility of the moist condensing vapour as well. Overheating of the evaporator in reference to the boiling temperature of diethyl ether at atmospheric pressure is 15K, the temperature difference between the evaporator and the condensation surface is equal to 25K.
In the Figure 5 shows the results of numerical analysis of the longitudinal component of compressible moist vapour velocity distribution within the Laval-like HP’s vapour channel at high heat loads. The formation of a condensing vapour toroidal ring vortex near the condensation surface inside of Laval-liked HP’s leads to quite interesting results. Toroidal vortex ring is a highly gradient zone of the condensable moist vapour velocity with the opposite directions inside and outside the vortex ring. The numerical analysis of the velocity distribution along the centerline of the vapour channel in the Laval-liked HP’s including the vortex ring shows the occurrence of two positive peaks of the velocity, one of them is in the critical section of the nozzle and the other near the condensation surface. In a critical section of the nozzle the axial component of velocity reaches 85 m/s, and near the condensation surface the counter-flow reaches the velocity of 33m/s. The distribution of the axial component of the moist vapour velocity shows the presence of a counter current due to the formation of a ring vortex within the vapour channel near the HPs condensation surface. This figure of the velocity distribution, shown in Figure 5, confirms the fact that the vortex ring is a zone of sharp velocity gradients, and as a consequence is also a pressure gradient. In the central part the vortex ring has a noticeable positive dynamic pressure, and it has a negative dynamic pressure in the peripheral part of the vortex ring. This means that lower static pressure occurs in the central part of the vortex ring and this leads to additional absorption of moist vapour in the condensation zone of Laval-liked HP’s.

![Figure 5](image_url)

**Figure 5.** The results of numerical analysis of the distribution of the vapour flow longitudinal velocity component inside the Laval-like HP’s vapour channel of compressible moist vapour at high heat loads.

4. Analytical results

Let’s consider the interaction of a vapour jet with a HP’s flat cover. The origin of the coordinate system is located at the intersection of the axis of the vapour channel with a HP’s flat cover, the z coordinate is measured in the direction opposite to the vapour jet direction. The gas dynamics equations in the Cartesian coordinate system describing the interaction of the unsteady viscous compressible vapour flow is described by the following equation:

\[
\frac{\partial Q}{\partial t} + \frac{\partial F}{\partial x} + \frac{\partial G}{\partial y} + \frac{\partial H}{\partial z} = 0 .
\]  

(1)
Equation (1) is supplemented by the ideal gas equation of state:

\[ P_{vp} = (\gamma - 1)\rho_{vp} \left[ e - \frac{(u^2 + v^2 + w^2)}{2} \right]. \]  

(2)

Vector of conservative variables \( \mathbf{Q} \) and vectors of vapour flows \( \mathbf{F}, \mathbf{G}, \mathbf{H} \) have the following form:

\[
\mathbf{Q} = \begin{pmatrix} \rho_{vp} \\ \rho_{vp} u \\ \rho_{vp} v \\ \rho_{vp} w \\ \rho_{vp} e \end{pmatrix}; \quad \mathbf{F} = \begin{pmatrix} \rho_{vp} u \\ \rho_{vp} u u + p - \tau_{xx} \\ \rho_{vp} u v - \tau_{xy} \\ \rho_{vp} u w - \tau_{xz} \\ (\rho_{vp} e + p) u - u \tau_{xx} - v \tau_{xy} - w \tau_{xz} + q_x \end{pmatrix},
\]

(3)

\[
\mathbf{G} = \begin{pmatrix} \rho_{vp} v \\ \rho_{vp} v u - \tau_{yx} \\ \rho_{vp} v v + p - \tau_{yy} \\ \rho_{vp} v w - \tau_{yz} \\ (\rho_{vp} e + p) v - u \tau_{yx} - v \tau_{yy} - w \tau_{yz} + q_y \end{pmatrix}; \quad \mathbf{H} = \begin{pmatrix} \rho_{vp} w \\ \rho_{vp} w u - \tau_{zx} \\ \rho_{vp} w v - \tau_{zy} \\ \rho_{vp} w w - p - \tau_{zz} \\ (\rho_{vp} e + p) w - u \tau_{zx} - v \tau_{zy} - w \tau_{zz} + q_z \end{pmatrix}.
\]

(4)

The components of the viscous stress tensor and the components of the heat flux vector are written in a standard way:

\[
\tau_{ij} = \mu_{eff} \left( \frac{\partial u}{\partial x_i} + \frac{\partial v}{\partial x_j} - \frac{2}{3} \frac{\partial u}{\partial x_i} \delta_{ij} \right); \quad q_i = -\lambda_{eff} \frac{\partial T}{\partial x_i}.
\]

(5)

In the above equations, \( t \) – time, \( s \); \( \rho_{vp} \) – the moist vapour density, \( \text{kg/m}^3 \); \( u, v, w \), \( \text{m/s} \), components of the vapour flow velocity in the coordinate directions \( x, y, z \) in the HP’s channel; \( p \) – pressure, \( \text{Pa} \); \( e \) – total energy per unit mass of moist vapour, \( \text{kJ/kg} \); \( T_{vp} \) – vapour temperature, \( \text{K} \); \( \gamma \) – specific heats ratio; \( \lambda_{eff} \) – effective thermal conductivity, \( \text{W/m·K} \); \( \mu_{eff} \) – effective viscosity is calculated in the standard way as the sum of molecular \( \mu \) and turbulent \( \mu_t \) viscosity.

\[
\frac{dM}{dt} = J_{vp}.
\]

(6)

where \( M \) – the increase in the mass of the condensed film in a unit of time, \( \text{kg/s} \); \( J_{vp} \) – the condensing vapour flow, \( \text{kg/s} \).

In the vapour flow braking area on the inner surface of the HP’s upper cover near the longitudinal axis \( r=0 \), the velocity of the vapour jets significantly reduced, in the turning and vortex formation section of the current lines are strongly curved. The thickness of the formed vortex is \( b \).

In the near-wall section (vortex area formation), the shear stresses \( \tau \) become dominant compared to normal ones \( \tau_n \). Spreading in the radial (and tangential) directions vapour jet loses momentum (amount of motion), the thickness of the boundary layer and the condensate film thickness \( \delta \) increase and the static pressure increases also. The calculation results show the occurrence of a large vortex formation formed in the mixing layer of the vapour jet in confined conditions of the vapour channel with HP’s flat cover surface. The vapour pressure pulsations Reynolds number \( \text{[4]} \) in the vapour channel nozzle throat reaches \( \text{Re}_{vp} \sim (1.5 - 1.65) \times 10^5 \), the Prandtl number \( \text{Pr} = 0.77 \).

Vortex structures have a determining effect on the heat exchange in the region of the vapour jets interaction with a flat HP’s end cap (flat wall). The heat transfer characteristics are non-uniform even at small values of the Reynolds number \( \text{Re}_{vp} \sim 5 \times 10^2 \). The Nusselt number \( \text{Nu} \) has a characteristic maximum at the braking point \( r=0 \), and the minimum value in the region of the vapour reversal at the periphery of the lid where the inverse (counter) vortex flow is formed \( \text{[10]} \).

The reasons for the heat exchange characteristics change in the vapour jets interaction point \( r=0 \) with the HP’s flat top cover and the appearance of a Nusselt number local maximum are explained by the formation
of a large-scale toroidal vortex [10] and a laminar-turbulent transition in the boundary layer and an
turbulence kinetic energy increase in the wall jets [11-12].

To describe the flows arising from the interaction of a vapour jets with HP’s flat top cover, the Navier–
Stokes equations (averaged over the Reynolds number) are usually used, in solving which the shortcomings
of various turbulence models are apparent manifested. In the event of vapour toroidal vortices, an additional
source of turbulence energy generation of the condensed vapour occurs due to the large curvature of the
current lines near the HP’s condensation surface.

To take into account the curvature of the current lines of the moving vapour near the condensation surface
in the toroidal vapour vortex formation and a more complete assessment of the turbulent energy generation,
the so – called Kato-Loner correction [13] is used, which is an additional source of turbulent energy in the
toroidal vortex vapour flow forming, that can be written in both integral and differential form [13]. This
increases the stability of the iterative process, although the time-averaged characteristics of the flows were
studied.

Figure 3 and Figure 4 shows a simplified diagram of a condensable vapour flow, is included in the inner
hole of a vapour toroidal ring vortex of radius r v , with a temperature T v and axial component velocity u v
and tangential component velocity v v . We consider the circumferential ( tangential) component of velocity in
the Laval-liked nozzle vapour channel is not equal to be zero. Static vapour pressure at the inlet of toroidal
vapour ring vortex is equal to P 0 , the cylindrical coordinate system is used.

As a main model variant, to simplify the analysis we consider the stationary state flow of a diethyl ether
film condensate between the stationary state vapour toroidal ring vortex and the flat surface of the HP’s top
cover. The vapour toroidal vortex ring and the condensate film move in the radial and tangential directions.
The task is to determine the thickness δ f of the diethyl ether condensate film under the toroidal ring vortex.

The proposed mathematical model uses the principle of the Karman and Pohlhausen [14-15], the basic idea
of which is the feasibility of the differential equations system on average thickness of the boundary layer δ,
as which the thickness of the condensate film δ f is considered. The peculiarity of the problem under
consideration is that the longitudinal and tangential components of the vapour flow velocity are commensurate.

Therefore, the momentum theorem is applied twice—for radial and circumferential directions of the
vapour flow:

\[ \frac{d}{dt}( \rho v_p (u^2_r - u^2_f) r \delta_{\phi}^{*} ) + \rho v_p r u_r \frac{d(u v - u_f)}{dr} \delta_{\phi}^{*} - \rho v_p (v_v - v_f)^2 \delta_{\phi}^{*} - 2 \rho v_p v_f (v_v - v_f) \delta_{\phi}^{*} = r \tau_{rs} . \]  

(7)

where \( u_v, v_f \) — components of the condensate film flow velocity under the vapour vortex in the radial
and tangential coordinate directions, m/s; \( u_v, v_f \) — radial and tangential vapour velocity in the
vapour vortex, m/s; \( \delta_{\phi}^{*} \) — the hydrodynamic thickness of the diethyl ether condensate film under the
vapour vortex ring, m, in general depends on the vapour flow rate; \( \delta_{\phi}^{*} \) — the condensate film thickness of
flow momentum loss due to the friction in the radial direction, m; \( \delta_{\phi}^{*} \) — the condensate film displacement
thickness, taking into account the displacement of the current lines in the condensate film due to the viscosity
of working fluid, m; \( \tau_{rs} = \mu (du/vz) - \delta_{\phi}^{*} \) — radial shear friction stress on the outer surface of condensate film under the vapour vortex ring, Pa.

Momentum conservation equation for tangential (circumferential) direction of the condensate film flow
look like this:

\[ \frac{d}{dr}( \rho v_p u^2 (v_v - v_f) \delta_{\phi}^{**} ) = r^2 \tau_{\phi\delta} . \]

(8)

where \( \tau_{\phi\delta} = \mu (dv/vz) - \delta_{\phi}^{**} \) — tangential shear friction stress on the outer surface of the condensate film
under the vortex ring, Pa; \( \delta_{\phi}^{**} \) — the condensate film thickness of flow momentum loss due to the friction in the
radial and tangential directions, m.

The thicknesses of the liquid condensate film \( \delta^{*} \) and \( \delta^{**} \) are determined in the standard way [16-17]:

\[ \delta^{*} = \int_0^\delta \left( 1 - \frac{\partial u_f}{\partial u_v} \right) dz ; \delta^{**} = \int_0^\delta \frac{\partial u_f}{\partial u_v} \left( 1 - \frac{\partial u_f}{\partial u_v} \right) dz . \]
where $\rho_l$ – the density of liquid condensate, kg/m$^3$.

Equations (7) and (8) contains more than two unknowns, therefore additional physically based linking equations are needed. The velocity vector deviates from the geometric radial direction, and the degree of deviation in the flux core and near the surface of the film are different.

Tangential (circumferential) vapour velocity $v$ in the flux core in the Laval-liked nozzle vapour channel we can define in the simplest way:

$$v_{v_{\text{m}}} = vr_{v_{\text{p}}}$$

where $m$ is a numerical parameter of unity order; $r_v$ –the inner radius of the toroidal vapour vortex, m.

The relationship between the pressure, density and temperature of the condensing vapour in the first approximation can be given by the ideal gas equation of state in the following form:

$$\rho_{v_{\text{p}}} = \frac{p}{RT}; T = T_v \left( \frac{p}{P_v} \right)^{(k-1)/k}; \rho_{v_{\text{p}}} = \frac{p}{P_v}$$

where $R = 8.3144$ J/mol·K – universal gas constant; $k = 1.31$, – value of the adiabatic index of diethyl ether vapour; $T_v$ –the temperature of the steam inside the toroidal vapour vortex, K; $\rho_v$ –the vapour density inside the toroidal vortex, kg/m$^3$; $P_v$ –the vapour pressure inside the toroidal vortex, Pa.

\[
\delta^*_q = \int_0^S \left( 1 - \frac{\rho u_{v_q}}{\rho_{v_{v_{q}}}} \right) dz; \delta^*_q = \int_0^S \rho u_{v_{q}}^2 \rho_{v_{v_{q}}} dz; \delta^*_{r_{qp}} = \int_0^S \rho u_{v_{q}} \left( 1 - \frac{\rho v_{q}}{\rho_{v_{v_{q}}}} \right) dz. \tag{9}
\]

\[
\delta^*_q = \int_0^S \left( 1 - \frac{\rho u_{v_q}}{\rho_{v_{v_{q}}}} \right) dz; \delta^*_q = \int_0^S \rho u_{v_{q}}^2 \rho_{v_{v_{q}}} dz; \delta^*_{r_{qp}} = \int_0^S \rho u_{v_{q}} \left( 1 - \frac{\rho v_{q}}{\rho_{v_{v_{q}}}} \right) dz. \tag{9}\]

\[
\delta^*_q = \int_0^S \left( 1 - \frac{\rho u_{v_q}}{\rho_{v_{v_{q}}}} \right) dz; \delta^*_q = \int_0^S \rho u_{v_{q}}^2 \rho_{v_{v_{q}}} dz; \delta^*_{r_{qp}} = \int_0^S \rho u_{v_{q}} \left( 1 - \frac{\rho v_{q}}{\rho_{v_{v_{q}}}} \right) dz. \tag{9}\]

Figure 6. The calculated values of the diethyl ether vapour density $\rho_{v_{\text{p}}}$ in the HP’s vapour channels along the longitudinal axis $z$ at the overheating $\delta T = (T_{ev} - T_B)$ of HP’s evaporators, with reference to the boiling temperature of diethyl ether $T_B = 308.65$ K (35.5°C) at atmospheric pressure, equal to the $\delta T = 15$K, with the temperature difference between the evaporators and the condensation surface equal to 25K. 1– solid line, the vapour density in the Laval-liked vapour channel at a pressure $P = 6.1 \cdot 10^5$ Pa; 2– dotted line, the vapour density in the HP with cylindrical vapour channel.
After integrating the differential equation (7) for the vapour core flow in the HP’s Laval-liked vapour channel along the radius \( r \) and taking into account the equation of state (10), we obtain an equation to estimate the vapour pressure distribution over the radius \( r \) in the vapour core flow:

\[
\frac{P}{P_v} = \left[ 1 + \frac{(k-1)}{k} \frac{1}{RT_v} \left( \frac{u^2 - u_v^2}{2} + \frac{v^2 - v_v^2}{2m} \right) \right]^{k/(k-1)}.
\]  

From the continuity equation of the vapour flow in the integral form we obtain the following relation:

\[
\rho_v u_r r^2 = \rho_{vp} u_r (r - \delta_r).
\]

where \( b \) – the thickness of the vapour toroidal ring vortex, m.

From this relation, taking into account the density \( \rho_v \) from (7) and (8), an equation can be obtained to estimate the radial velocity in the core of the vapor flow at the inlet to the vapour toroidal ring vortex:

\[
u = \frac{u_v^2}{r(b - \delta_r)} \left[ 1 + \frac{(k-1)}{k} \frac{1}{RT_v} \left( \frac{u^2 - u_v^2}{2} + \frac{v^2 - v_v^2}{2m} \right) \right]^{k/(k-1)}.
\]

In general, the vapour flow in the Laval-liked vapour channel is swirling flow, which is due to both the uneven jet character of vaporization in the evaporator and the variable cross-section of the vapour channel in the HP’s. For swirled vapour flows, the spin parameter is the determining parameter characterizing the ratio between the circumferential (tangential) and longitudinal (axial) velocity components in the HP’s vapour channel. To determine the local twist of the condensing vapour flow through the thickness of the liquid condensate film (boundary layer), the parameter of the local spin angle is used [18]:

\[\tan \phi = \frac{v_v}{u_v} = \varepsilon(r, z).
\]

where \( \tan \phi \) –parameter of spin angle.

Within the variable thickness of the of liquid condensate film under vapour toroidal ring vortex parameter of local twist \( \tan \phi \) depends on the radius on the flat surface of the HP’s condensation top cover and the linear parameter of the film thickness \( z \). At the vapour flow core, in the diffuser part of the vapour channel \( \tan \phi_0 \) parameter characterizes the degree of deviation of the vapour flow from the radial direction:

\[\tan \phi_0 = \frac{v}{u} = \varepsilon(r)_0.
\]

where \( \tan \phi_0 \) –parameter, defining the degree of deviation in the diffuser part of the HP’s vapour channel from the radial direction.

The liquid condensate film, formed under the vapour toroidal ring vortex, due to surface interfacial friction is fond of it and moves in the radial and tangential directions on the HP’s condensation flat surface. The parameter \( \tan \phi_{\text{max}} \) represents the limiting (surface) tangent of the twist angle of the formed liquid condensate film and is the ratio of surface shear stresses of friction in tangential (circumferential) and radial directions on the surface of the film of condensate of variable thickness and can be expressed as follows:

\[\tan \phi_{\text{max}} = \varepsilon(r)_{\text{max}} = \frac{\tau_v}{\tau_s}.
\]

The distribution of the circumferential velocity component in the turbulent liquid condensate film under the vapor toroidal ring vortex according to the Nikuradze's experiments results [17] can be represented as the following parabolas family:

\[\frac{v_r}{v_v} = \left( \frac{z}{\delta_v} \right)^n,
\]

where the exponent of the parabolas’ \( n \) depends on the Reynolds number \( \text{Re}_v \) of the vapour flow and changes in the interval \( 1/6...1/10 \) (0.17 –0.1).
The radial component of the liquid condensate film velocity $u_r$ under the vapor toroidal vortex ring can be defined as follows:

$$u_r = \frac{t_g \varphi \chi (v_v - v_r)}{\chi} = \frac{t_g \varphi}{\chi} \left( \frac{z}{\delta_f} \right)^n.$$  \hspace{1cm} (17)

where $t_g \varphi$ – twist parameter of the surface layer of the liquid condensate film, formed on the HP's condensation surface under the vapour toroidal vortex; $\chi$ – friction parameter of the toroidal vapour vortex ring.

The twist parameter $t_g \varphi$ decreases within the thickness of the condensate $z$, varies according to the quadratic parabola law [16, 17]:

$$t_g \varphi = \varepsilon - (\varepsilon - \chi) \left( 2 - \frac{z}{\delta_f} \right) \frac{z}{\delta_f}.$$  \hspace{1cm} (18)

where $\varepsilon$ – the tangent of the limiting (surface) angle of twist of the vapour flow is the ratio of surface shear stresses of friction in the circumferential (tangential) and radial directions on the condensate film surface.

In the equations for the momentum conservation of the vapour moving (7) and (8), the projection of the radial and tangential friction stress $\tau_s$ on the condensate film surface must be determined. To do this, we use the Prandtl hypothesis [17], which is the basis of a two-layer flow model, including condensing two-phase vapour, introduce a criterion for the stability $\beta$ of liquid condensate film flow under the vapour toroidal ring vortex ring in the form of a two-dimensional vector with magnitude of the shear stress $\tau_s$ (with components $\tau_{\varphi s}$, $\tau_{rs}$) on the film surface in the form of the following equation:

$$\beta = \frac{\tau_{\varphi s}}{\mu_l} = 11.65; \quad \tau_s = \sqrt{\tau_{\varphi s}^2 + \tau_{rs}^2}.$$  \hspace{1cm} (19)

where $\beta$ – the numerical value of the criterion of liquid film condensate flow stability under the vapour toroidal ring vortex; $\mu_l$ – kinematic coefficient of diethyl ether (liquid) viscosity, m²/s.

The limit value of the liquid condensate film thickness $\delta_f$ of diethyl ether under the toroidal vortex ring can be determined from the condition of velocities equality of the external surface of the film condensate and the toroidal vapour ring vortex. Given that the tangential component of the liquid film velocity under the condition of HP’s sticking at condensation surfaces ($v = 0$) can be written in the form:

$$u_r = \frac{\tau_{\varphi s}}{\mu_l} \frac{z}{\delta_f}.$$  \hspace{1cm} (20)

so we can write the following equation for the film of liquid condensate:

$$\frac{\tau_{rs}}{\mu_l} \delta_f = u_r + (u_v - u_r) \frac{\delta_f}{\delta_f} \left( \frac{z}{\delta_f} \right)^n.$$  \hspace{1cm} (21)

where $\mu_l$ – dynamic coefficient of diethyl ether viscosity, Pa·s; $\delta$ – condensate film thickness at immovable (stationary) vapour, m.

Measurements of the film flow rate were carried out earlier [7-8], the solution of this equation is as follows:

$$\delta_f = \left( \frac{u_v - u_r}{\frac{\delta_f}{\delta_f}} \right)^{\frac{1}{1-n}} \left( \frac{\mu_l}{\tau_{rs}} \right)^{\frac{1}{(1-n)}}.$$  \hspace{1cm} (22)

After replacing the limit $\delta_f$ in equation (22), we can obtain an expression for the radial component of shear stress $\tau_{rs}$ on the outer surface of the condensate film:
where Re_δ_– is the Reynolds number, defined by the thickness and a radial velocity component u_ψ of the diethyl ether condensate film flow.

The friction coefficient at the interfacial surface is determined in a standard way using the Blasius ratio:

\[ \tau_{rs} = \frac{u_r^2}{2} \rightleftharpoons \rightleftharpoons \chi_f = \frac{0.664}{(u_r/\nu_f)^{1/2}} \approx 10^{-2} \pm 10^{-1} . \]  

When film condensation on the horizontal surface of the HP’s top cover projection of gravity on the film flow direction is zero, and the provision of shear motion of the film occurs only due to the dynamic effects of vapour flow moving along the outer surface of the film. Motion in a thin film is considered to be inertialess.

Measurement outcomes for the time-averaged values of the diethyl ether layer thickness on the smooth condensation surface inside vapour channel depending on the heat load on the HP’s evaporator are shown in Figure 7 [7-9]. A non-linear and sharply decreasing dependence of the thickness of the liquid condensate film δ_f on the HP’s top cover in dependence of the HP’s evaporator’s overheating compared to the boiling point of diethyl ether at atmospheric pressure δ_T = T_ev – T_b, while the absolute error of the thickness measuring does not exceed 1·10^{-3} mm.

At low thermal loads and the flow of the vapour vortex from the periphery to the center of the vapour channel, condensate film has a large thickness. As the heat load on the HP’s evaporator increases, the direction of the vortex flow changes to the opposite, the direction of vapour and condensate film flow become wake (in one direction), and the film thickness begins to decrease sharply.

\[ \text{Figure 7. Dependence of averaged values of the diethyl ether layer thickness on the condensation surface on the HP’s condenser overheating in reference to the boiling temperature of diethyl ether } \delta_T = T_ev – T_b , \text{K, at a semi-logarithmic scale.} \]

The typical experimental dispersion of measurements of the average values of the condensate film thickness ~ 1·10^{-3} mm noticeably increases starting the overheating value δ_T ~ (11÷12) K, when a boiling process starts in the capillary porous HP’s evaporator and the vapour becomes humid.

The Reynolds number of the moving film of diethyl ether with thickness δ = 10^{-2} mm, \( \nu_f = 0.032 \cdot 10^{-4} \text{ m}^2/\text{s} \), Prandtl number Pr = 0.77, at equal velocities of the vortex (30 m/s) and the film is equal to:

\[ \text{Re}_\delta = \frac{u_r \delta}{\nu} = \frac{3 \times 10^{-2} \text{ m/s}}{0.032 \cdot 10^{-4} \text{ m}^2/\text{s}} = 0.94 \cdot 10^2 . \]
The calculated values of the film thickness are in the range of $10^{-2} \div 10^{-4}$ mm when the value of friction coefficient is $c_f = 10^{-2} \div 10^{-3}$, condensing vapor Reynolds number $Re_{vp} = 10^3 \div 10^4$ and the vortex velocity up to 30 m/s. That is close to the experimentally obtained values of the film thickness of the diethyl ether condensate [7-9].

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