HEAT TRANSFER FROM SMALL SIZE HEATERS TO A FALLING LIQUID FILM

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ABSTRACT

Experimental investigation of heat transfer from local heat sources to a falling film of light boiling dielectric liquid perfluorotriethylamine is carried out. The liquid temperature is below the saturation temperature. The presence of air in a vapor phase provides the opportunity of temperature and surface tension change on a film surface. Some experimental data for heaters of various sizes are presented. The experimental data are compared with the results obtained previously for various liquids and with known calculation relationships. A model of heat transfer from a local heater to a smooth liquid film until the regular structures formation is proposed. The thermocapillary effects, the influence of dependence of liquid viscosity on temperature and the effect of heater sizes on the heat transfer are analyzed.

1. INTRODUCTION

Film devices, in which the liquid falls down the inner surface of vertical tubes have been widely used in the low-pressure evaporation equipment of food production industry [1]. The intensity of heat transfer under evaporation increases as the thickness of the liquid film decreases. It is, however, impossible to use a very thin film, because the probability of its breakdown, which causes a heat transfer crisis, increases. Flowing down films are subjected to wave processes caused by their instability. This leads to non-uniform spraying and large thin film areas of laminar flow, at sufficient large average liquid flow rates. To simulate the processes at the lower parts of tubes of evaporation apparatus it is necessary to study the heat transfer in thin liquid films. There are, however, practically no investigations on the heating of liquid films at small Reynolds numbers (Re<10).

The primary task of improvement of low pressure evaporators is the intensification of heat and mass transfer processes and the increasing of falling film stability to against breakdown. To enhance the heat transfer in real apparatus, a spinning motion of the liquid film is created, and a gas is injected into the flow. As the liquid flows tangentially, the centrifugal force leads to complete wetting of the tube surface. Also the use of finned surfaces is a way to enhance film evaporation. The effect of microfins on evaporation was considered in [2]. Surfaces with larger fins are also used [3, 4]. Non-uniform heating of non-smooth surfaces is peculiar to films flowing down such surfaces. Non-uniform heating of the liquid also takes place under wave motions of films. The non-uniform heat flux on the inside surface of a smooth tube can be caused by the fins on the outside surface. In practice, fins can be of various sizes and have different locations. Therefore it is important to investigate the effects of the heaters sizes on the hydrodynamics and heat transfer in the liquid film.

The hydrodynamics and heat transfer in flowing down liquid films has been widely studied in the literature. Many aspects of this problem were considered in books of Alekseenko et al. [5] and Gimbutis [6] as well as in review [7]. In many cases film motion is essentially influenced by the Marangoni effect caused by the temperature gradient and by the component concentration gradient. The Marangoni effect can be essential for heat transfer under laminar flow regimes of the film and under laminar-wave flow regimes in the film areas with smooth thin residual layer separated nonstationary solitary waves. Influence of the Marangoni convection can cause the loss of flow stability, thinning and breakdown of liquid film, sharp worsening of heat transfer and heat transfer burn-out. In the majority of the published papers the insufficient attention is given to a case, when heat is transferred from the non-uniformly heated substrate to a liquid layer.

Papers [8, 9] are practical unique exceptions, where thermocapillary convection is investigated in gravitationally falling thin liquid film heating from a local source of heat. In this experiments the phenomenon of regular structure formations have been discovered on the local heater for flowing films of 25% ethyl alcohol solution in water. By direct measurements of the temperature of the interface with the help of infrared thermography it was proved that the structures are of a thermocapillary nature. An experimental investigation of the heat transfer from a local heat source with sizes 6.5×13 mm to falling film of the dielectric liquid perfluorintriethylamine (MD-3F) has been made in [10, 11]. The flow pattern map was offered. The critical heat flux densities for small Reynolds numbers was measured. The effects on heat transfer of such factors as the viscosity of the liquid and the sizes of the heaters had not been considered earlier.

In present study the data for heaters with two different sizes are obtained. A comparison of the experimental data with the results obtained previously for various liquids and with known correlation is carried out. A model of heat transfer from a local heater to a smooth liquid film until the regular structure formation is proposed. An analysis of the thermocapillary effects, the influence of liquid viscosity - temperature relation and the effect of heaters sizes on the heat transfer is made.
2. EXPERIMENTAL SETUP

The scheme of experimental setup is shown in Fig.1. The apparatus includes the closed circulating loop and the tank for preliminary heating of a working liquid by a thermostat 1. The liquid is supplied by the electro pump. The setup has a system for final heating of the liquid by two heat exchangers connected with a thermostat 2. The heat exchangers 1 and 2 are constructed in accordance with a "tube in tube" scheme. Such design allows to supply on an entrance of rotameters a liquid always at identical temperature 25°C. The test section is placed in hermetic chamber made of organic glass with wall sizes 15-30 mm. A tubular heat exchanger-condenser is also placed in the chamber. The composition of the vapor-gas mixture in the zone of measurement of heat transfer was controlled by sampling of the gas from the chamber with the help of a microsyringe 3 and its subsequent analysis.

The experiments were performed for perfluorotriethylamine (MD-3F). This liquid is ecologically harmless, not dangerous for human health, and has some important properties. Low values of the boiling point (70.35°C) and of the latent heat of the phase transition make it possible to investigate critical processes and the dynamics of dry spots without damaging the heating elements. The use of perfluorotriethylamine (a pure liquid, not soluble in water, with a low value of surface tension) allows one to avoid the effects of surface-active substances, uncontrollable impurities, and "accidental" ruptures. At the same time, the fact that the surface tension depends strongly on the temperature makes it possible to investigate to full measure the thermocapillary effects of the process. The liquid film is formed by a flat nozzle 4 on top part of the plate. The liquid, flowing down the plate, is accumulated in the receiver 5, and is returned to the reservoir with a pump under the action of gravitation.

The experimental researches of heat transfer from local heaters with sizes of 4.02×68.1 mm and 2.22×68 mm are executed. The initial temperature of the liquid varies from 20 to 30°C. The Reynolds number varies within the range of 1-20. The experimental method is described in detail in [9, 10]. The cavity with depth of approximately 2 mm around the heaters is filled with a mixture of epoxy resin and charcoal. The 2.5 mm thick layer of this mixture also covers the surface around the heater of 85×200 mm in size. Each source of heat allows to measure local values of heat flux densities in two different points. The thermocouples on the heater of 4.02×68.1 mm are located at distances of 1.55 and 2.6 mm from the upper edge, and the thermocouples on the heater of 2.22×68 mm are located at distances of 0.88 and 1.67 mm, respectively. Special calibration experiments at natural convection on both heaters were performed to check the method of measurements. The work chamber in these experiments was filled with the liquid. The temperature of the liquid in the work chamber was 27-30°C. Test experiments on the heat transfer in the initial region of formation of the thermal boundary layer with a liquid film flowing down a vertical or inclined surface in the absence of the Marangoni effect (Re = 20) were also carried out. The data obtained are in satisfactory agreement with the results known for free convection and liquid film flow.

All used thermocouples had individual calibration and allowed to measure temperature with an error 0.1°C. At $\Delta T_{\text{w}} \geq 2^\circ\text{C}$ an experimental error of a local heat flux measurement was no more than 7.7%. The liquid flow rate was measured with an error no more than 1.5%.

3. ANALISIS OF EXPERIMENTAL DATA

Figure 2 shows a comparison of experimental data with the data obtained in works [9-11] for water, 25% ethyl alcohol in water solution, and MD-3F. Calculation from dependence

$$Nu_F = 2.06 \left[ 1 + 0.0443 \left( \frac{\text{Pe}_F \ h_F}{X_T} \right)^{4/3} \right]^{1/4}$$

recommended in [6] for laminar and laminar-wave film flow at condition on the wall $\nu^*=\text{const}$ is also presented in the Fig. 2. Experimental data are presented for different heat flux densities from 0.9 to 19.7 W/cm². Figure 2 presents also theoretical solutions for the initial heat transfer region (large $\text{Pe}_F$, inclined straight line) and for stabilized heat transfer ($\text{Pe}_F \rightarrow 0$, horizontal line) [6]. The properties of the liquid were calculated by $T_F$. The experimental data at heat flux densities 0.9 < $\nu$ < 3.8 W/cm² and $\text{Pe}_F$ > 200 deviate from the Eq. (1) by no more than 15 %. The deviation is somewhat larger at the greatest values of $\text{Pe}_F$. This can be explained by the effect of the initial hydrodynamic region. At a heat flux density of 19.7 W/cm², the deviation of the experimental data from the Eq (1) increases and one is systematic. This can be a consequence of the fact that the properties of the liquid depend on the temperature. It is proposed in [6] to use the following correction to take into account the change in the physical properties of the liquid due to the temperature:

$$Nu_F = 2.06 \left[ 1 + 0.0443 \left( \frac{\text{Pe}_F \ h_F}{X_T} \right)^{4/3} \right]^{1/4} \left( \frac{\text{Pr}_F}{\text{Pr}_{F0}} \right)^{0.25}$$
The decrease in the viscosity of the liquid caused by a temperature increase also leads to a decrease in the film thickness and enhancement of heat transfer.

It will be suggest, that the viscosity does not vary considerably with the thickness of the film, but mainly depends on the temperature $T_F$ that is a function of the longitudinal coordinate. A linear temperature dependence is assumed for the surface tension coefficient.

The stabilized heat transfer in a thin liquid film falling on a vertical plate is considered. The liquid film flows along the $x$-axis under the action of gravitation. The plate is perpendicular to the $y$-axes. It will be considered as a first approximation, that the width of heater $B$ in the direction $z$ perpendicular to the liquid flow is great enough, and the liquid velocity in the direction of the $z$-axis is equal to zero. Also, the deformations of the free surface of the film are assumed to be small. The Nusselt task for viscous film flow is used.

$$\frac{\partial}{\partial y} \left( \nu \frac{\partial \theta}{\partial y} \right) + g = 0 \quad (3)$$

At the wall ($y=0$) $u=0$. At the free surface $y=h(x)$, taking into account the Marangoni effect, there is condition of equality of tangential stresses

$$\mu \frac{\partial u}{\partial y} - \frac{d\sigma}{dT} \frac{\partial T}{\partial x} = 0 \quad (4)$$

The velocity distribution is obtained below under the condition of small deformation of the free surface. If we assume that the viscosity depends only on $x$, the longitudinal velocity component is described by the following relation:

$$u = \left( \frac{g}{\nu} + \frac{1}{\mu} \frac{d\sigma}{dT} \frac{dT}{dx} \right) y - \frac{g}{2\nu} y^2 \quad (5)$$

For the liquid flow rate in the film at the heater and, accordingly, before the heater we have

$$\Gamma_v = \int_0^{h(x)} dy \tau_{sur}, \quad \Gamma_{0v} = \int_0^{h_0} dy = \frac{gh_0^3}{3\nu_0} \quad (6)$$

The liquid flow rate in film is constant and equal to the initial flow rate until the onset of a reverse flow at the film surface. Using (5) and (6) for the film thickness, the following algebraic expression is received

$$\left( \frac{h}{h_0} \right)^3 + \frac{3}{2} K_{T0} \left( \frac{h}{h_0} \right)^2 = \frac{v}{v_0} \quad (7)$$

Here

$$K_{T0} = \frac{d\sigma}{dT} \frac{dT(x)}{dx} = \frac{d\sigma}{dT} \frac{dT}{dx} \frac{v}{v_0^2} \left( \frac{3\nu}{g} \right)^{2/3} = \frac{\tau_{sur}}{\tau_{w}} \quad (8)$$

Parameter $K_{T0}$ was obtained in [12] in an empirical analysis of the experimental results on the regular structures formation. It has given good results in generalization of the data on threshold heat flux density at the spontaneous onset.
of periodic vertical rivulets. The Eq. (7) and parameter $K_{T0}$ for the case $\mu=\text{const}$ were analyzed in [14].] It is the ratio of tangential stress on the surface of the flow, caused by thermocapillary force, to tangential stress on the wall, caused by the falling film in the absence of thermocapillary forces.

Assuming that the velocities of the liquid in the directions $y$ and $z$ are negligibly small, we write the equation of energy conservation in the following form:

$$u \frac{\partial T}{\partial x} = \alpha \left( \frac{\partial^2 T}{\partial y^2} \right)$$  \hspace{1cm} (9)

The following initial and boundary conditions are used: at $x=0$ $T=T_0$, at $y=0$ $q=q_w$, and at $y=h$ $q=0$. In accordance with [6], it follows from the heat balance for $q_{w}=\text{const}$ that

$$\frac{\partial T}{\partial x} = \frac{d T_F}{dx} = \frac{q_w}{c T} = \frac{q_w}{c p \nu \text{Re}} = \frac{d T}{dx}_{\text{sur}}$$  \hspace{1cm} (10)

where bulk film temperature in section $x$ is described by expression

$$T_F = T_0 + \frac{q Y/(c T)}{h} \int_0^h u(y) T(x, y) dy$$  \hspace{1cm} (11)

We assume that the surface temperature gradient is also constant (10). Substituting the values of velocity and $d T/dx$ into Eq. (9) and integrating it twice with respect to $y$, the temperature distribution in the film is received

$$T = \frac{q_w}{c a T} \left( A \frac{y^3}{6} - B \frac{y^4}{12} - C y + D + a x \right)$$  \hspace{1cm} (12)

Here the coefficients are determined from boundary conditions.

The heat transfer coefficient and the Nusselt number are determined as follows:

$$\alpha_F = \frac{q_w}{T_w - T_F}, \quad \text{Nu}_F = \frac{\alpha_F h_0}{\lambda}$$

For the Nusselt number the following expression is obtained

$$\text{Nu}_F = \frac{1 + \frac{3}{2} \left( \frac{h}{h_0} \right)^{-1} K_T}{15 \frac{h}{24 h_0} + \frac{39}{280} \left( \frac{h}{h_0} \right)^4 + \frac{1 - \frac{33}{80} \left( \frac{h}{h_0} \right)^3}{10 \left( \frac{h}{h_0} \right)^4} K_T - \frac{3}{10} \left( \frac{h}{h_0} \right)^4 K_T^2}$$  \hspace{1cm} (13)

In this expression the dimensionless criterion $K_T$ contains the properties of the liquid at temperature $T_F$. The Eq. (13) shows, that at this problem statement $\text{Nu}_F$ depends only on the criterion $K_T$ and the ratio of the liquid film thickness in the region of measurement of heat transfer and the initial thickness of the film. At $K_T=0$ and $h=h_0$, the following well-known relation [6] for stabilized heat transfer at small Reynolds numbers is obtained from (13):

$$\text{Nu}_F = 2.06$$  \hspace{1cm} (14)

Experimental data obtained for various heaters at $\text{Re} \leq 12$ and the calculation by Eqs. (13) and (7) for the case of negligibly small variation in viscosity (line 1) are presented in Fig. 3. The relation (14) and the results of calculations by using the Eq. (1) for MD-3F at $\text{Re} = 12$ are given for the sake of comparison. It is seen that the Eq. (13) is lower than all experimental data and the relations (1) and (14). The dashed and dashed-dotted lines show the results of calculations by using Eqs. (13) and (7) for 25% solution of alcohol in water and MD-3F, where $\mu$ at the point of measurement of heat transfer is calculated by $T_F$ and could differ considerably from $\mu_0$. It is seen that allowance for the effect of viscosity leads to an increase in the intensity of heat transfer. An analysis of the Eq. (13) shows that the thermocapillary forces determined by the criterion $K_T$ have a fundamental effect on the heat transfer. At high heat fluxes, the Nusselt number decreases by a factor of 4 and more. The effect of the viscosity-temperature relation leads to a decrease in the thermocapillary action on the heat transfer and to an increase in $\text{Nu}_F$ up to 40%. Whereas the experimental data for long heaters are located near the curve mentioned above, they are much higher for a heater of 6.5 x 13 mm.

Enhancement of heat transfer at a liquid film flows over a heater of small size can also be influenced by the liquid flow in the lateral direction due to the action of...
thermocapillary forces. The tangential stress directed across the flow on the surface of the liquid film is calculated as follows:

\[ \tau_z = \frac{\partial \sigma}{\partial x} = \frac{\partial \sigma}{\partial T} \frac{\partial T}{\partial x} = \frac{\partial \sigma}{\partial T} \Delta T \] (15)

We assume that the heater is wide enough so that the liquid flow rate in the lateral direction is much smaller than the flow rate in the longitudinal direction. Then \( \Delta T \) is estimated as the difference between the temperatures \( T_T \) and \( T_0 \), and \( \Delta x \) is determined by the expression \( \Delta x = B/2 \), where \( B \) is the width of the heater. Hence, we obtain

\[ \tau_z = \frac{\partial \sigma}{\partial T} \frac{2q_w}{\Gamma cB} \] (16)

The liquid flow under the action of only tangential stress is realized in the direction \( z \):

\[ \frac{\partial^2 u_x}{\partial y^2} = 0 \] (17)

At the wall (\( y=0 \)) \( u_x=0 \) (18)

At the film surface \( y=h(x) \) boundary condition taking into account the Marangoni effect can be written in the following form:

\[ \mu \frac{\partial u_z}{\partial y} = \tau_z = \frac{\partial \sigma}{\partial T} \frac{2q_w}{\Gamma cB} \] (19)

We obtain for the flow velocity in \( z \) direction:

\[ u_z = \frac{\partial \sigma}{\partial T} \frac{2q_w}{\Gamma cB\mu} \] (20)

The volumetric flow rate of the liquid in the lateral direction is determined by the following relation:

\[ Q_x = 2 \int_0^{x_T} \int_0^{h(x)} u_x \, dx \, dy \] (21)

The calculation is made for the case when the point of the heat transfer measurement is located in the center of the heater \( (X_T=L/2) \). It should be noted that one should take into account the dependence of \( \mu \) on \( x \) or use its average value at sufficiently high heat fluxes for liquids whose viscosity depends strongly on the temperature. We have

\[ Q_x = \frac{q_w h^2 L^2}{4\Gamma cB\mu} \frac{\partial \sigma}{\partial T} = \frac{3q_w h^2 L^2 v_0}{4\rho c B\mu} \frac{h_0^3}{\Delta T} \] (22)

From the condition of liquid mass conservation next equation is obtained

\[ \Gamma_1 B = \Gamma_0 B - Q_x \] (23)

It follows that

\[ \left( \frac{h}{h_0} \right)^3 + \frac{3}{2} K_{T_1} \left( 1 + \frac{L}{B} \right)^2 \frac{v/v_0}{1 + v/v_0} \left( \frac{h}{h_0} \right)^2 = \frac{v}{v_0} \] (24)

The result of a calculation of \( h/h_0 \) by using Eqs. (13) and (24) is shown Fig. 3. The effect of transverse sizes for a heater of 6.5 \( \times \) 13 mm \( (L/B = 0.5) \) does not explain the higher intensity of heat transfer. The effect of relative sizes of a heater on the heat transfer can be considerable at \( L/B > 1 \). The result of a calculation by using the Eqs. (13) and (24) for \( L/B = 2 \) is shown in Fig. 3. The Nusselt number increases by 20\% in comparison with the one of the calculations for \( L/B = 0 \). The simplified analysis carried out above cannot, clearly, reveal all peculiarities of the complex process under consideration. It shows only an estimate of the effect of the three non-dimensional parameters \( (K_T, \nu/v_0, L/B) \) on the heat transfer in a liquid film.

Photographs of an MD-3F film flowing down a plate with a heater of 6.5 \( \times \) 13 mm are shown in Fig. 4. They show that large-scale three-dimensional dynamic deformations appear in the film in a wide range of \( Re \) numbers. These deformations change the average integral thickness of the liquid film and could result in heat transfer enhancement. The available equipment, however, detected the dynamic cellular formations in flow regimes only until the onset of stable regular structures. Such deformations were not observed for long heaters of 4.02 \( \times \) 68.1 mm and 2.22 \( \times \) 68 mm.

The cellular dynamic deformations could result from the three-dimensional instability of the liquid film due to the effect of the heater sizes, the interference of hydrodynamic waves that existed in the experiment [10, 11] at \( Re \geq 2 \) and the vertical instability that caused the onset of regular structures. Whereas for a heater of 6.5 \( \times \) 13 mm the large-scale three-dimensional dynamic deformations resulted in the formation of stable structures with dry areas between the rivulets, a thin liquid film remained between the rivulets in the case of long heaters. The cellular dynamic structures possibly resulted in enhancement of non-stationary evaporation of the liquid in the areas of film thinning. These questions should be studied in further investigations.

Figure 4. The regimes of perfluorethylamine film flow under the conditions of a considerable Marangoni effect.
5. CONCLUSIONS

1) The effects of the sizes of local heaters on the heat transfer of a liquid film flowing down a vertical surface were investigated. It has been shown that at Peclet numbers less than 200 the known relations that describe the heat transfer for long heaters are not valid for local heaters.
2) A model of the heat transfer from local heaters to a smooth liquid film until the formation of regular structures is proposed. A calculation was carried out that described the effects of thermocapillary forces, the viscosity-temperature relation, and the sizes of the heaters. The results of the calculation explain, on the whole, the actual tendency in the variation of the Nusselt number as the heat flux increases.
3) Only the decrease in the heat transfer due to thermocapillary thickening of the liquid film is, however, described satisfactorily. Allowance for the viscosity-temperature relation and evaluation of the lateral liquid flow across the heating element under action thermocapillary forces does not explain the enhancement of heat transfer observed experimentally.

Acknowledgments

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NOMENCLATURE

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<th>Symbol</th>
<th>Description</th>
<th>Units</th>
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<tr>
<td>a</td>
<td>thermal diffusivity of the liquid</td>
<td>m²/s</td>
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<tr>
<td>B</td>
<td>heater width</td>
<td>m</td>
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<tr>
<td>c</td>
<td>thermal capacity of the liquid</td>
<td>J/(kg K)</td>
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<tr>
<td>h</td>
<td>film thickness</td>
<td>m</td>
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<tr>
<td>g</td>
<td>gravitational acceleration</td>
<td>m/s²</td>
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<tr>
<td>Kp, KT</td>
<td>criteria, dimensionless</td>
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<tr>
<td>L</td>
<td>heater height</td>
<td>m</td>
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<tr>
<td>NuF</td>
<td>Nusselt number, dimensionless</td>
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<tr>
<td>q</td>
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<td>Re</td>
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<td>T</td>
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<tr>
<td>TW</td>
<td>wall temperature</td>
<td>°C</td>
</tr>
<tr>
<td>u</td>
<td>velocity of liquid</td>
<td>m/s</td>
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<td>x, y, z</td>
<td>Cartesian coordinates, m</td>
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<tr>
<td>XF</td>
<td>distance from the upper edge of the heater to the point of the heat transfer measurement</td>
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Greek symbols

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<tr>
<th>Symbol</th>
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<tr>
<td>α</td>
<td>local heat transfer coefficient</td>
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<td>liquid mass flow rate</td>
<td>kg/m s</td>
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<td>λ</td>
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<td>μ</td>
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<td>ν</td>
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<td>ρ</td>
<td>density of the liquid</td>
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<td>σ</td>
<td>surface tension coefficient</td>
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<td>τsur</td>
<td>tangential stresses on the film surface</td>
<td>N/m²</td>
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Subscripts

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<tr>
<td>F</td>
<td>value determined at temperature TF</td>
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<td>W</td>
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</tr>
<tr>
<td>0</td>
<td>initial parameters of flow</td>
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