Heat transfer calculation under film and drop condensation on tube with heat intensifiers

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Abstract. This article discusses well-known models and equations for calculating the heat transfer gain during film and drop condensation on a pipe, which need to be improved. Film condensation heat transfer on horizontal pipe made from brass with knurling is analyzed. The heat transfer data for investigated steam mixture condensation on horizontal tube with spikes heat intensifiers is analyzed. It is noted that the functions of drop growth for various conditions and their distribution must be known for calculating heat transfer during drop condensation. The maximum droplet radius, droplet size distribution, and then condensation heat transfer performance could be adjusted with special condensing surfaces, such as gradient, superhydrophobic, grooved, hydrophobic-hydrophilic patterned and hybrid surfaces. Now the nanoscale structures can by nanotechnologies.

1. Introduction
At present there are models and equations for calculating heat transfer enhancement at film and drop condensation on the tube, however, they need to be improved [1-13].

2. Heat transfer intensification at film condensation
The heat transfer intensification in the case of film condensation on the outer surface of horizontal pipe with grooves is attributed to the action of surface tension on the condensate film. The film falls into the grooves, and as a result its thickness on the remaining decreases. This effect is enhanced by decrease in the relative pitch of grooves. The thickness of the condensate film on protrusions on the pipe surface and its thermal resistance decreases. The fall of the condensate into grooves decreases the film stability and leads to its stalling. The redistribution of the condensate along the pipe length leads to a growth of the average heat transfer coefficient. In contrast to finning, knurling allows to increase heat transfer on both outer and inner pipe surfaces.

The film condensation heat transfer was investigated by G A Dreitser [6] on a horizontal pipe made from brass with knurling (Figure 1). It was established that the heat transfer coefficient for a knurled pipe increased more than two times (Figure 2). The heat transfer enhancement is higher if the grooves are deeper and the pith is smaller, as well as the radius of the rounding of the protruding parts of the pipes.
Figure 1. Horizontal profiled pipe.

Figure 2. Film condensation heat transfer on horizontal pipe made from brass with knurling (2) and plane surface (1) [6].

In work [6] the data on film condensation heat transfer for pipes with heat intensifiers were described by dependences that take into account the effect of principal parameters in investigated conditions.

\[ \frac{\alpha}{\alpha_{film}} = 2.47 \left( 1 - \frac{R}{D_H} \right) \left( 1 - 0.38 \frac{r}{D_H} \right) e^{3.65 \left( 1 - \frac{d_H}{D_H} \right)} \]  

(1)

In ranges \( \frac{d_H}{D_H} = 0.89-0.95; \frac{r}{D_H} = 0.283-0.37; \frac{R}{D_H} = 0.5-1. \)

Where heat transfer coefficient of film condensation on horizontal tube was calculated by Nusselt equation:

\[ \alpha_{film} = 0.73 \sqrt{\left( \lambda \right)^3 \rho g (\mu' (T_s - T_w)D_H)} \]  

(2)

The properties in equation (2) are determined under saturation temperature.

Heat transfer intensification in pipes located vertically is less manifested than in horizontally oriented pipes. The influence of knurling on heat transfer increases with Re_{film}, knurling depth, and
with a decrease in its pitch. When $Re_{\text{film}} < 400$, a decrease in $t/h$ below 8 accompanied by a further increase in the ratio of Nusselt numbers for pipes with knurling. This is explained by the retainment of condensate in grooves by the surface tension forces.

Visual observations and filming of the process of steam condensation on a pipe with annular grooves showed that at $Re < 500–700$ an increase in the heat transfer rate is caused by large-scale changes in the condensate film.

The condensation heat transfer may experience the influence of the wall material. The mechanism underlying this influence is the nonuniform distribution of the wall temperature in the case of a low heat conduction coefficient. The introduction of the dimensionless complex $\lambda_w\delta_w/(\lambda_{\text{film}}d_{\text{eq}})$, where $\lambda_w$ and $\lambda_{\text{film}}$ are the thermal conductivities of the wall material and film, $\delta_w$ is the wall thickness, and $d_{\text{eq}}$ is the equivalent diameter of the annular channel, allowed to correlate data on heat transfer in condensation of the vapors of gasoline and water in an annular channel by a single dependence.

The condensation heat transfer of steam mixture R113/H$_2$O was investigated on horizontal ribbed tube. The ribs and spikes on tube, produced by deformation method, proposed in Bauman University, are shown on Figure 3.

**Figure 3.** The ribs and spikes on tube, produced by deformation method, proposed in Bauman University [9]

The heat transfer data of Yu. B. Smirnov for the steam mixture condensation on horizontal tube with spikes were presented on Figure 4. The calculated heat transfer was shown for condensation of steam Freon-113 and his mixture with water on tube with diameter 16 mm with flat surface.

**Figure 4.** Heat transfer for condensation steam mixture R113/H$_2$O on horizontal tube with diameter 16 mm with spikes (3) and flat surface (1) under pressure 0.2 MPa (a) and 0.4 MPa (b) [9].
The heat transfer enhancement for tube with spikes that is not connected with surface development was equal 1.5 and 1.7 (Figure 4).

3. Heat transfer intensification at drop condensation

The wide range of drop sizes arose on condensing surface. The drop grows until it attains a maximum radius. Thus a certain drop size distribution function \( F(R) \) is established on the condensing surface. Both theoretical analysis and experimental investigation showed that dropwise condensation heat transfer coefficient decreased with the increase of the maximum droplet radius. The maximum droplet radius, droplet size distribution, and then condensation heat transfer performance could be adjusted with special condensing surfaces, such as gradient, superhydrophobic, grooved, hydrophobic-hydrophilic patterned and hybrid surfaces.

Heat transfer calculation of drop condensation is based on heat and mass balances for a single drop and empirical dependences for rate of drop and drop distribution on surface.

Upon contact of steam with surface is formed the adsorption layer, then the polimolecular liquid film arises that is under proppant pressure. The proppant pressure is inversely about a cube of film thickness. The local film thinning leads to increase of proppant pressure compared with neighboring plots. The liquids is crowded out to adjacent plots, that are more than an effective radius of action of intermolecular forces. The equilibrium pressure of saturated steam over convex surface of interface section is more than flat. The steam condensation on spherical drop with radius \( R \) can arise only under condition that \( R > R_d \), where \( R_d \) – critical (minimal possible) radius of interface surface curvature. A lot of drops whose radius is changed from critical \( R_d \) to departure \( R_o \) can form on the wall in every moment in general case. Continuous growth of drops through steam condensation and drop fusion is compensated by forming primary and disappearance of the grand drops.

The functions of drop growth and their distribution need to know for condensation heat transfer calculation. These functions need to know for different conditions.

In work [2] it was shown that drop condensation heat transfer increases with growth of centers condensation density and with decrease of drop diameter departure \( R_o \):

\[
\alpha \approx N^{1/4} R_0^{-1/2}
\]  

(3)

The centers condensation density \( N \) in equation (3) is determined by

\[
N = \text{const} \left( \frac{r \rho \Delta T}{\sigma_s} \right)^2
\]  

(4)

The constant in equation (3) is equal \( 10^{-4} \).

The functions of drop growth and their distribution on drop diameter departure \( R_o \) was shown on figure 5.

Now the nanoscales structures can produce by nanotechnologies. So by change the relief it can change the wetting angle. The increase of surface that is in contact with vapor leads to the heat transfer intensification under condensation.

The average heat transfer under drop condensation on horizontal tube can calculate through equations V P Isachenko (Figure 6) [3]. The parameter \( \xi \) describes the change of surface tension from temperature gradient. According to calculation the heat transfer coefficient under drop condensation can be to 10 times more then under film condensation. The maxima on dependence \( \alpha(\Delta t) \) is explained as follows. First with growth \( \Delta t \) the steam supersaturation increases and the condensation is intensified. By that the thermal resistance of condensate is not grand. The increase of condensation rate and condensate on surface lead with increase \( \Delta t \) to decrease the heat transfer owing to the effect of thermal resistance is more.

If in steam there is air or other non-condensing gases the condensation heat transfer decreases strong.
Figure 5. Functions of drop distribution [2]: 1-4 – calculation through proposed method: $T_s=334$ K, 2,4 – $T_s=393$ K, experimental data: 6-8 – $T_s=393$ K, 9-11 – $T_s=373$ K, 12-14 – $T_s=334$ K.

Figure 6. Average heat transfer coefficient under drop and film condensation on horizontal tube under different pressures [3].
Conclusions
Heat transfer enhancement under film and drop condensation on pipe was considered. The data on condensation heat transfer on horizontal pipe with different heat transfer enhancement and plane surface were discussed.

The models and equations for calculation of heat transfer enhancement under film and drop condensation were considered. The functions of drop growth need to know for condensation heat transfer calculation. These functions need to know for different conditions.

The maximum droplet radius, droplet size distribution, and then condensation heat transfer performance could be adjusted with special condensing surfaces, such as gradient, superhydrophobic, grooved, hydrophobic-hydrophilic patterned and hybrid surfaces.

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