Heat transfer during boiling in a thin horizontal layer of the dielectric liquid

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Abstract. This paper presents the results of the experimental study of heat transfer in horizontal layers of dielectric fluid HFE–7100 with a height of 2.5, 6.0 and 10 mm at pressures of 100 kPa and 50 kPa on a smooth surface ($R_s = 3.2 \mu m$). It is found that the Gogonin formula correlates well with experimental data on heat transfer coefficients for HFE-7100 layers of different heights. The values of the critical heat flux obtained at various pressures are close to the calculated values according to the Yagov model in the layer with the height of 10.0 mm. A decrease in the height of the HFE–7100 layer led to a decrease in the values of the critical heat flux.

1 Introduction

The most important purpose of thermophysics is the search for new methods of heat transfer enhancement and ensuring stable and safe operation of heat transfer equipment. Boiling and evaporation are the most effective ways to remove heat from the hot surface. The growing number of studies devoted to the search for methods to increase the heat transfer coefficient (HTC) and critical heat flux (CHF) at boiling shows the high interest of the scientific community in this topic. This is due to the fact that there is no closed mathematical description of the bubble boiling process at the moment, and only the experiment remains the main data source.

Currently, the practical application of the boiling process has become especially relevant for cooling microelectronics. Compared to an air cooling system, a two-phase system can reduce the use of additional equipment, such as cooling pumps and fans, while reducing the amount of electricity consumed. The approach is based on the fact that electronic components are immersed in a closed tank filled with liquid. When the surface temperature of the electronic components exceeds a certain temperature, the liquid begins to boil and intense heat transfer occurs. The produced vapor rises up, condenses through a water-based condenser and drips back into the tank driven by gravity [1, 2]. The use of dielectric liquids is due to the low saturation temperature (~30–65°C). The permissible heating temperature of heat-generating microelectronics elements is (~80–85°C) [3]. Various studies performed at pool boiling conditions have shown high efficiency of dielectric fluids for cooling microelectronics [4-6].

The obvious disadvantage of immersion two-phase system cooling is the high consumption of quite expensive liquid, which is necessary to fill the large tank for immersing the electronic components into that one. Thin layers of liquid can significantly reduce the consumption of coolant and reduce the weight and size characteristics of heat transfer equipment. At the moment, the influence of the height of the liquid layer on heat transfer and CHF is not sufficiently represented in the literature. The study of the characteristic transitions from heat transfer during boiling in thin horizontal layers of liquid to heat transfer during pool boiling is a particularly important research task for the design of future highly efficient cooling systems. A brief overview of studies on heat exchange during boiling in horizontal layers of various liquids is presented in [7].

2 Experiments

A detailed description of the experimental stand is given in [8, 9]. The working chamber is made in the form of a cylindrical vessel made of 12X18H10T steel with a wall thickness of 1 mm, an inner diameter of 120 mm and a height of 300 mm. Heating of the bottom of the working chamber is carried out by an electric heater with a power of 2 kW. To measure the heat flux 5 holes with a diameter of 1.5 mm are drilled in the bottom side at different heights, into which copper–constantan thermocouples are inserted in stainless capillaries. The heat flux is calculated using the Fourier equation from the temperature gradient measured along the center line of the upper part of the bottom, using a linear approximation of the output signal of five thermocouples. The relative errors of heat flux and HTC did not exceed 15%.

Methoxynonafluorobutane (HFE-7100) C₄F₉OCH₃ was used as the working fluid. Molar mass of liquid $M = 250$ g/mol. Table 1 presents formulas for...
calculating the thermophysical properties of HFE-7100 [10, 11]. Table 2 shows the values of the thermophysical properties of HFE-7100 at pressures of 100 kPa and 50 kPa.

Table 1. Formulas for calculating the thermophysical properties of HFE-7100.

<table>
<thead>
<tr>
<th>Thermophysical property</th>
<th>Calculation formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid density, kg/m³</td>
<td>( \rho_l(T) = a_0 + a_1 \cdot T + a_2 \cdot T^2 + a_3 \cdot T^3 ), where ( a_0 = 2510.64 ); ( a_1 = 5.68904 ); ( a_2 = 1.32655 \times 10^{-3} ); ( a_3 = 1.80161 \times 10^{-5} )</td>
</tr>
<tr>
<td>Vapor density, kg/m³</td>
<td>( \rho_v(T) = \frac{P(T) \cdot M}{T \cdot R} )</td>
</tr>
<tr>
<td>Saturation pressure, Pa</td>
<td>( P(T) = \exp \left( 22.415 - 3641.9 \cdot \frac{1}{T} \right) )</td>
</tr>
<tr>
<td>Latent heat of vaporization, J/kg</td>
<td>( h_f(T) = a + b \cdot P(T) ), where ( a = 1.173 \times 10^5 ); ( b = 0.056 )</td>
</tr>
<tr>
<td>Kinematic viscosity, m²/s</td>
<td>( \nu(T) = \nu_0 \cdot \exp\left( \nu_1 \cdot T^{-1/2} + \nu_2 \cdot T + \nu_3 \cdot T^{-3/2} \right) ), where ( \nu_0 = 85.44 \times 10^{-5} ); ( \nu_1 = -1859.99 ); ( \nu_2 = 0.009152 ); ( \nu_3 = 0.001297 )</td>
</tr>
<tr>
<td>Surface tension, N/m</td>
<td>( \sigma = \sigma_0 \cdot (1 - T_f(T_f(T) \cdot T_c)^{T_f})^{1/3} \cdot (1 + \sigma_1 \cdot (1 - T_f(T) \cdot T_c)^{T_f})^{1/3} ), where ( T_f = T/T_c ); ( T_c = 468.45 ); ( \sigma_0 = 49.351 ); ( \sigma_1 = 0.0527 )</td>
</tr>
<tr>
<td>Heat conduction, W/(mK)</td>
<td>( \lambda(T) = -0.00019548 \cdot (T - 273) + 0.073714 )</td>
</tr>
<tr>
<td>Specific heat capacity, J/(kg K)</td>
<td>( C_p(T) = 2 \cdot (T - 273) + 1133 )</td>
</tr>
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</table>

Table 2. The thermophysical properties of HFE-7100 at different pressures.

<table>
<thead>
<tr>
<th>Thermophysical property</th>
<th>( P, ) kPa; ( P/P_c )</th>
<th>100 (4.5 \times 10^2)</th>
<th>50 (2.2 \times 10^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_s ), ºC</td>
<td></td>
<td>61</td>
<td>41</td>
</tr>
<tr>
<td>( \rho_s ), kg/m³</td>
<td></td>
<td>1419</td>
<td>1474</td>
</tr>
</tbody>
</table>

Before starting the experiments, a certain amount of working fluid was poured into the bottom of the working chamber, necessary to create a layer of the desired height. The liquid was degassed by boiling at low pressure for several hours. During the experiments a number of stationary heat transfer modes were implemented, in which temperatures along the thickness of the heated wall and pressure above the liquid layer in the volume were recorded.

3 Results and discussion

In this paper the effect of the height of the dielectric liquid layer on the heat transfer at boiling for pressures of 100 kPa and 50 kPa was considered.

Figure 1 shows the dependences of the heat flux on the temperature head obtained in layers with height of 2.5, 6.0 and 10.0 mm at pressures of 100 kPa and 50 kPa. It was found that a lower temperature head was achieved in the 2.5 mm layer compared to higher layers at all pressures. At a pressure of 50 kPa in the layer of 10.0 mm in the pre-crisis heat transfer mode the temperature head reached the value of 33 K, which meets the requirements for cooling microelectronics [3]. The CHF value strongly depended on the height of the liquid layer. The crisis in the 2.5 mm layer occurred at a low heat flux. The CHF values in the 6.0 mm and 10.0 mm layers differed by about 1.5 times.

It is shown in [12, 13] that the exponent for the number Re* must be taken equal to 0.8. The calculated dependence [10, 11] for pool boiling has the form:

\[
Nu = 0.01 Re^{0.8} Pr^{1/3} \frac{K^3}{R_s^{1/2}} \left( \frac{\lambda_c \rho_l}{h \rho_p \nu} \right)^{1/3} \left( \frac{\lambda_c \rho_l}{h \rho_p \nu} \right)^{1/3},
\]

where \( Nu = \frac{a_d l_{pl}}{\lambda} \) – Nusselt number; \( Re = \frac{ql_{pl}}{h \rho_p \nu} \) – Reynolds number; \( Pr = \frac{\nu}{a} \) – Prandtl number;

\( a = \frac{\lambda}{\rho \mu} \) – thermal diffusivity, m²/s; \( K_e = \frac{h_{e \rho}}{c_p T \rho \sigma} \) – criterion of thermal similarity, \( b = 1 + 10 \left( \frac{\rho_l}{\rho_e - \rho_l} \right)^{2/3} \) – dimensionless complex; \( l_e = \left( \frac{\sigma}{g (\rho_e - \rho_l)} \right)^{1/3} \) – capillary constant of the...
liquid, $m = \frac{R}{l} = \text{dimensionless roughness}$, \(g\) – acceleration of gravity, $m/s^2$. Parameters $\lambda_w$, $c_{pw}$, $\rho_w$ relate to the thermophysical properties of the heat-emitting wall.

The most well-known calculated dependence for heat flux is the Rohsenow formula [14]. The ratio describing the heat transfer during the pool boiling of organic liquids:

$$q = 0.16 h_0 \sqrt{\frac{g(\rho_c - \rho_v)}{\sigma}} \cdots$$  \hspace{1cm} (3)

Figure 2 shows a comparison of experimental data with dependences (1) and (2). From Figure 2 it can be seen that dependence (1) has a high correlation with experimental data on heat transfer at the pressure of 100 kPa. Dependence (2) weakly correlates with experimental data. Varying the $C_{sf}$ value does not bring a satisfactory result, since the exponent at the value of the heat flux is clearly greater than in formula (2), and corresponds to 0.8, as proposed in formula (1).

It is known that CHF is the most important safety parameter for most systems that use boiling. The reviews [15, 16] provide a large number of models for calculating the CHF in various conditions, including those obtained using neural networks. However, at present there are no reliable calculation methods for the value of CHF in thin layers of liquid.

To estimate the value of the CHF, consider the well-known models of the boiling crisis in a large volume of liquid.

1) Kutateladze hydrodynamic crisis model [17]:

$$q_{cr} = \left( q_{cr,v} + q_{cr,h} \right)^{1/3},$$  \hspace{1cm} (4)

where $q_{cr,v} = \frac{h(\rho_c - \rho_v)}{\sigma} \cdots$  \hspace{1cm} (5)

Figure 3 shows a comparison of experimental data with dependencies (3) and (4). It can be seen from Fig. 4 that at a pressure of 100 kPa the CHF value in a layer with a height of 10.0 mm was obtained between the calculated values (3) and (4). At a pressure of 50 kPa the crisis value is accurately described by the formula (4).

In thinner layers the CHF values were significantly less than in the 10.0 mm layer at all pressures.
The height of the liquid layer affected the nature of the boiling crisis. Thus, in the 2.5 mm layer, a dryout crisis was observed, during which a dry spot formed in the center of the heating surface (Fig. 4 (a)). In the 6.0 mm and 10.0 mm layers a hydrodynamic crisis was observed, in which the liquid layer was pushed away from the heating surface by a vapor film. At the same time, bubbles of the same diameter were formed in the layer at a distance corresponding to the wavelength of the Rayleigh-Taylor instability (Fig. 4 (b)). In [8] this type of crisis was observed when using n-dodecane.

Fig. 2. Comparison of experimental data obtained in liquid layers of different heights at pressures of 100 kPa and 50 kPa with dependences: 1 – Gogonin formula (1) [13]; 2 – Rohsenow formula (2) [14].

Fig. 3. The dependence of CHF on the related pressure in HFE-7100 layers of different heights: 1 – Kutateladze’s formula (3) [17]; 2 – Yagov’s formula (4) [18].

Fig. 4. Photos of the boiling crisis obtained at pressure 100 kPa: (a) – a dryout crisis in the layer with the height of 2.5 mm, \( q = 45.5 \text{ kW/m}^2, T_w - T_s = 30 \text{ K} \); (b) – a hydrodynamic crisis in the layer with the height of 6.0 mm, \( q = 99.5 \text{ kW/m}^2, T_w - T_s = 49.6 \text{ K} \).

4 Conclusion

This paper presents the results of a study of heat transfer and critical heat fluxes during boiling in horizontal layers of the dielectric liquid HFE-7100 of various heights. It is found that the Gogonin formula correlates well with experimental data on heat transfer coefficients for HFE-7100 layers of different heights.
In a layer with the height of 10.0 mm at the pressure of 100 kPa the CHF value of 151 kW/m² was achieved. At the pressure of 50 kPa the CHF value of 99 kW/m² was achieved. The experimental data obtained in the 10.0 mm layer correlate with the Yagov formula for calculating the CHF. In thinner layers of liquid lower values of CHF were obtained due to the development of the surface dryout crisis.

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References

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