Dynamics of propagation of a self-sustained evaporation front on the flat and cylindrical heaters

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Abstract. The paper presents the results of experiments on freons R21 and R114 and their mixtures. The variation range of volatile component concentration is 0 < C < 1. The propagation velocity of a self-sustaining evaporation front was studied. The experiments were carried out under the conditions of free convection at a temperature of saturation. The stainless steel tubes with the diameters of 3 and 8 mm and a flat section of 25 x 50 mm were used as the working sections. The experimental results showed that in the field of development of hydrodynamic instability of a vapor front, a higher velocity of front propagation corresponds to a higher concentration of volatile component. Experiments with different heater geometry showed that dependence of the evaporation front velocity on the temperature head for a cylindrical heater with a diameter of 3 mm almost coincides with the dependence for a flat heater. In the region of temperature heads corresponding to the loss of hydrodynamic stability of the evaporation front interface, an earlier development of instability is observed on a heater with a diameter of 8 mm.

1. Introduction
Unsteady heat generation in a local section of the heat exchanger can cause significant overheating of liquid heat carrier contacting with the heated wall and lead to formation and propagation of a vapor film. The vapor film spreads due to heat accumulated in the metastable liquid layer. Many authors suggest various models for propagation of a self-sustaining evaporation front. The models, as a rule, consider propagation of the undisturbed evaporation front [1, 2]. Only in some cases, the authors considered the influence of small-scale perturbations of the interface on propagation dynamics of the evaporation front [3]. In [4, 5], the authors consider the shape of interface of a self-sustaining evaporation front without taking into account small-scale disturbances. In recent years, there is a tendency of using mixtures as the working fluids in refrigeration machines, heat pumps and thermal transformers instead of single-component liquids [6]. The ozone-safe non-azeotropic mixtures of refrigerants R32/R134a and R32/R152a are considered in [7] as well as heat transfer at boiling in the horizontal tubes. The purpose of this work is an experimental study of dynamics of a self-sustaining evaporation front and development of hydrodynamic instability of disturbances on the interface in R21, R114 freons and mixtures of R21 - R114 freons on the heaters of different geometries.

2. Setup and description method
The experimental setup is a cylindrical vessel with a diameter and height of 250 mm with built-in windows for visualization of processes. Freon R21 on the saturation line under the pressure of 0.27 - 0.28 MPa was used as a working fluid. In the experiments, horizontally oriented cylindrical working sections made of tubes (diameter of 8 mm, wall of 0.2 mm, length of 50 mm, and diameter of 3 mm,
wall of 0.5 mm, and length of 50 mm) and vertically oriented flat rectangular working section with a width of 25 mm, length of 50 mm, and thickness of 0.2 mm were used. The material was stainless steel. The roughness of the section with a diameter of 3 mm was represented by multidirectional risks with a width of not more than 10 µm and individual smoothed cavities with a diameter of 30-50 µm. The roughness of the flat and 8-mm diameter working sections is represented by randomly oriented grains of 10-100 µm in size with an arbitrary shape. A high-speed video camera was used to observe the dynamics of evaporation front. The shooting speed was 25,000 frames per second with an exposure of 25 µs. The heat-generating surface was heated by a rectangular current pulse of a given duration and amplitude. To illuminate the object in transmitted and reflected light, the LED assemblies with a luminous flux of 9000 lm were used; the moment of their switching-on was synchronized with the moment of heat generation beginning. A detailed description of setup and experimental technique is given in [8].

3. Results and discussions
The dependence of propagation velocity of a self-sustaining evaporation front $V_{fr}$ on the temperature of wall overheating with respect to the temperature of liquid saturation $\Delta T = T - T_s$ is shown in Figure 1. Data are given for a cylindrical heater with a diameter of 3 mm. The experiments were carried out using the mixture of R114/R21freons. Molar concentration (C) of R114 freon in the mixture was varied from 0 (C = 0, pure R21) to 1 (C = 1, pure R114). Concentration C = 0.62 corresponds to the azeotropic point. For the given concentration, volatilities of both components of the mixture are equal.

![Figure 1. Evaporation front velocity vs. temperature difference. $P = 0.27$ MPa: a – cylindrical heater of 3 mm, R114/R21 mixture, concentrations C = 0 (1); 0.1 (2); 0.2 (3); 0.35 (4); 0.62 (5); 1.0 (6)](image)

As it can be seen from the diagram, dependence $V_{fr}$ ($\Delta T$) has two characteristic regions: the region of weaker dependence (region 1) and the region of stronger dependence (region 2). In [8,9], the presence of region 2 is associated with the development of hydrodynamic instability of Landau. The loss of stability by interface perturbations on the scale of the thermal layer thickness leads to heat transfer intensification through the interface and, as a consequence, to an increase in the front velocity.

In the region of weaker dependence, there is no significant difference in the velocity of front propagation. In region 2, the experimental data are substantially stratified, depending on concentration of the R114 component in the mixture. At the same values of temperature head $\Delta T$, the velocity of
Evaporation front propagation is greater in the mixture with a higher concentration of the R114 component. From the standpoint of development of instability of small-scale disturbances, the effect of a higher front velocity in the mixture can be explained by the fact that the vapor counter-pressure is a destabilizing factor, and capillary forces are a stabilizing factor. For freon R21 under the conditions of experiments, the vapor density is 11.46 kg/m³, and the surface tension coefficient is 0.0163 N/m. For the 62% mixture of R114 - R21, it is 16.84 kg/m³ and 0.012 N/m, respectively. That is, in the mixture, instability develops at lower vapor velocities, and, consequently, lower temperature heads \( \Delta T \).

Dependence \( V_f(\Delta T) \) for the cylindrical heaters with the diameters of 3 and 8 mm is shown in Figure 2. As it can be seen in the diagram, the development of hydrodynamic instability is observed on the heater with the diameter of 8 mm at smaller temperature head \( \Delta T \) than on the heater of the 3-mm diameter. This effect is observed for freon R21 and freon mixtures at the azeotrope point. Earlier development of instability on the heater of the 8-mm diameter may be related to the curvature of the working section and requires instability analysis not in the Landau formulation for an infinite plane, but in a formulation that takes into account interface curvilinearity of the interfacial surface. To test this hypothesis, the experiments were carried out on a flat working section.

![Figure 2](image_url)

Figure 2. Evaporation front velocity vs. temperature difference. \( P = 0.27 \) MPa. Cylindrical heater, R114/R21 mixture, concentrations \( C \): 1 – \( D = 8 \) mm, \( C = 0.62 \); 2 – \( D = 3 \), \( C = 0.62 \); 3 – \( D = 8 \), \( C = 0 \); 4 – \( D = 3 \), \( C = 0 \)

Dependence of the velocity of evaporation front propagation for the flat and cylindrical heaters is presented in Figure 3. The experiments were carried out on Freon R21 under equilibrium pressure \( P = 0.167 \) MPa. As it can be seen from the diagram, dependence \( V_f(\Delta T) \) for a flat heater and a heater with a diameter of 3 mm almost coincide. For all d series of experiments in region 1, there is no significant difference in the velocity of front propagation. At the front velocity of more than 2.5 m/s, the data for the flat and cylindrical heaters coincide also. The difference is observed only in the zone of hydrodynamic instability development. On the 8-mm heater, the development of instability starts earlier, when the temperature head reaches value \( \Delta T = 57 \) K. For the flat and cylindrical heaters with a diameter of 3 mm, transition to region 2 is observed at higher temperature heads (\( \Delta T = 62 \) K) than for the cylindrical heater with a diameter of 8 mm.
Figure 3. Evaporation front velocity $V_{fr}$ vs. temperature head $\Delta T$ for the flat and cylindrical heaters. Freon R21, $P = 0.167$ MPa: 1 – flat heater; 2 – cylindrical heater, $D = 3$ mm, 3 – cylindrical heater, $D = 8$ mm.

In region 2, at $\Delta T = 67$ K, the front velocity on all three heaters depends equally on the temperature head. Experimental data for different working sections are significantly stratified in the range of temperature heads $56 < \Delta T < 62$ K. On the flat and cylindrical heaters with a diameter of 3 mm, stabilization of propagation velocity of the evaporation front is observed in this temperature range, and only when $\Delta T = 62$ K, there is a loss of interface stability and more intense increase in velocity with increasing temperature head. On a cylindrical heater of the 8-mm diameter, loss of stability is observed at $\Delta T = 56$ K.

4. Conclusions
Experiments on propagation dynamics of a self-sustaining evaporation front in a mixture of R114/R21 freons showed that for the same temperature head $\Delta T$, the velocity of evaporation front propagation is greater in a mixture with higher concentration of the R114 component. From the standpoint of the development of instability of small-scale disturbances, the effect of a higher front velocity in the mixture can be explained by the fact that hydrodynamic instability in a mixture with higher concentration of R114 develops at lower values of temperature head $\Delta T$. The reason for the earlier development of instability is the difference in density and surface tension coefficient for different mixtures. For hydrodynamic stability of the interface, the vapor counter-pressure is a destabilizing factor, and capillary forces are a stabilizing factor. Experiments with different heater geometries showed that dependence of the evaporation front velocity on the temperature head for a cylindrical heater with a diameter of 3 mm almost coincides with dependence for a flat heater. In the region of temperature heads corresponding to the loss of hydrodynamic stability of evaporation front interface, the earlier development of instability is observed on a heater with a diameter of 8 mm.

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