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On the shape of self-sustained evaporation front in a metastable liquid

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Abstract. A theoretical model which takes into account new experimental data is proposed for the description of a stationary surface of the self-sustained evaporation front propagating in a layer of superheated liquid flowing over a flat heater. An approximate analytical dependence of the vapour layer thickness on the coordinate and physical parameters is obtained and found to satisfactorily agree with the experimental results. A dimensional parameter is introduced that allows the description to be presented in an invariant dimensionless form.

1 Introduction

Experiments on the heat exchange in boiling liquids have revealed a regime of interest for both basic science and technical applications, in which a vapor layer propagates over a cylindrical heater under conditions of liquid superheating above the boiling temperature at a given pressure [1-4]. Models proposed previously [1, 5-9] aimed at approximate description of the dependence of evaporation front propagation velocity on some set of physical parameters. Some of these models [5, 7, 9] suggest that a "frontal stagnation point" exists at the interface. However, some recent experimental data did not confirm the existence of the frontal stagnation point [2], which implies the need for developing a new approach to the description of these phenomena. In addition, the aforementioned models do not describe the shape of a stationary interface. In this context, the present work aims at developing the analytical description [10] of a stationary shape of self-sustained evaporation front propagating in a layer of superheated liquid flowing over a flat heater.

2 Description of the model

Reported shadow images [2] showed that the thickness of a vapor layer monotonically increases along the heater surface. In the frontal region, the interface is initially smooth. Thus the model assumptions are as follows. The flow is laminar, the flow velocity varies insignificantly, the curvature of the interface is small. Under these conditions, we can ignore the dynamic and surface pressure and assume that the liquid flows at a constant velocity over an almost flat free surface $y = f(x)$ with velocity V (in the frame of reference connected with evaporation front). The proposed model also ignores the following factors:

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hydrostatic pressure; compressibility and viscosity of phases; buoyancy, wettability, and thermocapillary effects; finite thickness of the interface; heat transfer between the vapor and the heater. It is also assumed that the evaporated liquid is subsequently not condensed. In the steady-state problem formulation, we will ignore variations of heater temperature T_W and heated-layer thickness δ_T (within the time interval under consideration) and consider the vapor layer as semi-infinite. It is taken into account that the ratio $\rho_V/\rho_L = \varepsilon$ is small ($\varepsilon << 1$), subscripts L, V refer to the liquid and vapor phases, correspondingly. Using Bernoulli integral, conditions of continuity at the interface (for material flow, energy flux, normal and tangential components of momentum flux), and also the balance between vapour production and vapour flow, the analytical solution (1) has been derived [10, 11], which describes the vapor layer thickness f depending on the coordinate x and main physical parameters ($\varphi = mx$, $g = mf$):

$$\varphi = (1 + g/2)\sqrt{g + g^2/4} - 2\,\mathrm{Arsh}\left(\sqrt{g}/2\right). \quad (1)$$

The solution is presented in an invariant dimensionless form with the unique parameter of the model: $m = \mathrm{Ja}^{-2}\,\pi V/a_L$, here $\mathrm{Ja} = c_p \Delta T/\varepsilon L$ is Jakobi number, a_L and c_p are the thermal diffusivity and heat capacity of the liquid, L is the evaporation heat, ΔT is overheating of the metastable liquid. According to the solution (1), the derivative $f_x \to \infty$ as $x \to 0$. The presence of this singularity does not mean that the model is principally inapplicable, since the integral fluxes of heat and vapour in any finite region of the interface remain finite. The dimensionality of the parameter m corresponds to inverse length V/a_L, and it characterizes the curvature of the interface along the coordinate x.

3 Discussion

The obtained analytical solution (1) doesn't take into account the curvature of the interphase surface along the transversal direction (z), which is about R^{-1} (R is radius of the cylindrical heater). Nevertheless, the solution (1) is applicable if R is large enough. Physically this condition means $R >> 1/m$. The plot of $f(x)$ calculated according to (1) for the case $m^{-1} = 20\,\mu\mathrm{m}$ (this value corresponds to the conditions of experiment [2] with Freon-21, $\Delta T = 76$ K, $V = 3.9$ m/s, $R = 1.5$ mm) is presented in the Fig. 1.

The comparison shows that solution (1) well describes the experimental data [2], except for some initial region of the interface with vapour layer thickness $g < 1$. It may be assumed that the stagnation zone with the closed stream lines is formed near the forward point $x = 0$. This is confirmed by the results of numerical modeling of the steady-state incompressible isothermal liquid flow (Fig. 2) along the non-deformable bottom ($y = 0$ at $x < 0$ and $y = f(x)$ at $x \ge 0$). The derivative of tangential velocity component along the normal direction at the bottom equals to null.

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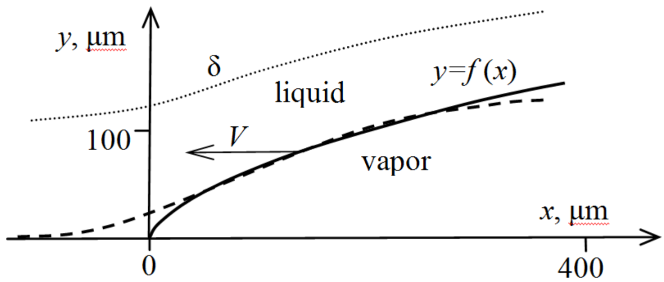

Fig. 1. Analytical solution *f* (*x*) (solid line) and experimental data [2]: the interphase surface (dash line) and the thermal layer (δ).

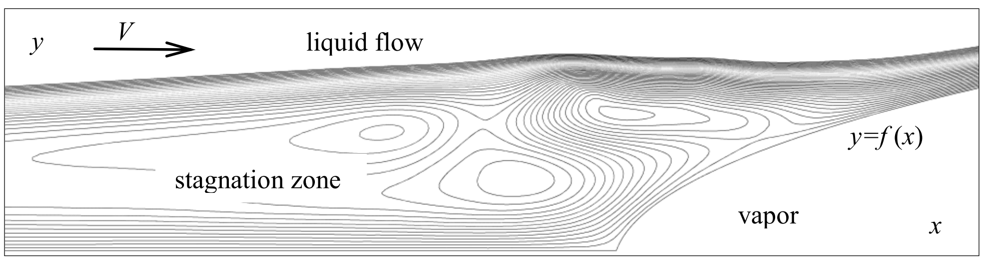

Fig. 2. Stream lines in the stagnation zone in liquid at the forward part of the interphase surface (numerical modeling), hydrodynamic parameters correspond to the conditions of the experiment [2].

The analytical solution (1) also provides good correspondence to the experimental data [12] with acetone ($\Delta T = 65$ K, $V = 7.1$ m/s, $1/m = 0.4$ mm $R = 1.25$ mm), see Fig. 3.

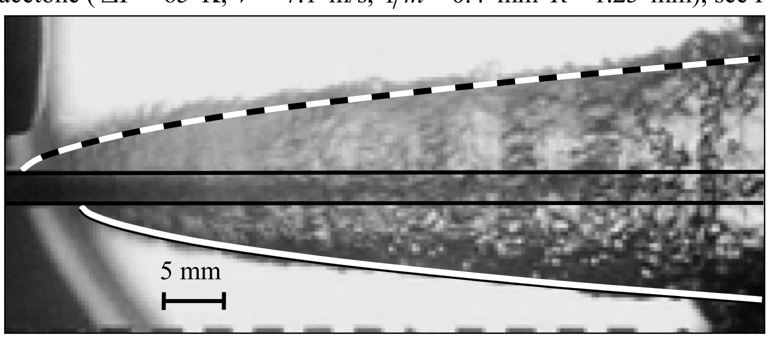

Fig. 3. Photo of the propagating vapor cavity – experimental data [12] and the analytical solution (1) (curves) with $1/m = 0.4$ mm.

The conditions of the experiments [13] with acetone also satisfy the inequality $R > 1/m$, and the obtained solution is close to approximations of the experimental data (here $\Delta T = 119$ K, $V = 25.5$ m/s, $1/m = 0.4$ mm $R = 1.25$ mm), see Fig. 4. According to [13], the thickness of the vapor cavity is proportional to $A_1 t^{0.66}$ ($t = x/V$) and the radius of the initial bubble is proportional to $A_0 t^{0.66}$ (approximate dependences). The analytical solution (1) has the same dependence: $g = (3\varphi/2)^{2/3}$ at the forward part, where $g << 4$. If we rewrite this in the form $f = Bt^{2/3}$, then the numerical value of the coefficient $B = 8.36$ $\mathrm{mm/ms^{2/3}}$ exceeds the value $A_1 = 5.14$ $\mathrm{mm/ms^{0.66}}$, but exactly equals to A_0.

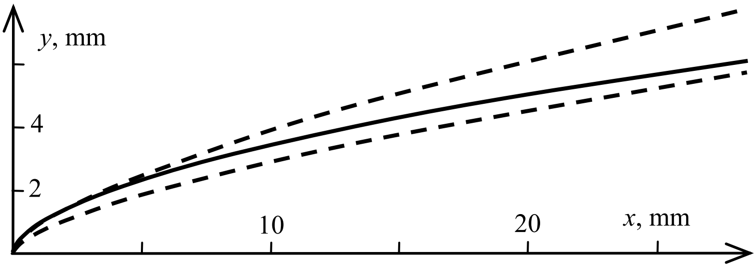

Fig. 4. The analytical solution (1) with $1/m = 0.4$ mm (solid line) and the approximations of experimental data [13] for the thickness of vapor cavity at the upper and lower parts of the surface of cylindrical heater (broken lines).

The solution (1) noticeably exceeds experimental data in case $R < 1/m$, when the curvature of the interphase surface in z direction can not be neglected comparatively with the curvature along x-axis.

4 Conclusions

The analytical dependence (1) of the vapor-layer thickness on the coordinate (derived in the framework of proposed approximate theoretical model of stationary propagation of the self-sustained evaporation front in a layer of superheated liquid flowing over a flat heater) satisfactorily agrees with the known experimental data for cylindrical heaters under the condition $R > 1/m$. The governing parameter m in physical sense plays the role of characteristic curvature of the interphase surface in the direction of evaporation front propagation. This stationary solution can be used as the base to study the problem of weak perturbation stability at the liquid-vapor boundary.

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References

1. B.P. Avksentyuk, V.V. Ovchinnikov, V.Ya. Plotnikov, Izv. Sib. Otd. Akad. Nauk, Ser. Tekh. Nauk. 17 (1989) [in Russian]
2. A.N. Pavlenko, E.A. Tairov, V.E. Zhukov, A.A. Levin, M.I. Moiseev, J. Eng. Thermophys. **23**, 173 (2014)
3. A. Stutz, J. R. Simoes-Moreira, Int. J. Heat Mass Transfer **56**, 683 (2013)
4. V. E. Zhukov, D.V. Kuznetsov, M. I. Moiseev, Innov. Nauka, 76 (2016)
5. B.P. Avksentyuk, Russ. J. Eng. Thermophys. **5**, 1 (1995)
6. B.P. Avksentyuk, V.V. Ovchinnikov, High Temp. **34**, 799 (1996)
7. A.N. Pavlenko, V.V. Lel', Thermophys. Aeromech. **6**, 105 (1999)
8. A.S. Moloshnikov, I.I. Shmal', High Temp. **38**, 53 (2000)
9. S.P. Aktershev, V.V. Ovchinnikov, J. Appl. Mech. Tech. Phys. **49**, 194 (2008)
10. O.V. Sharypov, Tech. Phys. Lett. **43**, 379 (2017)
11. O.V. Sharypov, Thermophys. Aeromech. **24**, (2017) (to be published)
12. B.P. Avksentyuk, V.V. Ovchinnikov, Thermophys. Aeromech. **15**, 267 (2008)
13. B.P. Avksentyuk, V.V. Ovchinnikov, Thermophys. Aeromech. **11**, 609 (2004)