Int. J. Heat Mass Transfer. Vol. 30, No. 9, pp. 1847–1857, 1987
Printed in Great Britain

0017-9310/87 $3.00+0.00

Dissipative model of film boiling crisis

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(*Received* 18 *July* 1986)

Abstract—A dissipative model of the film boiling crisis based on the variational hypothesis of non-equilibrium phase change is presented. Transfer systems—characteristic for film and transition boiling of a liquid droplet on a plane horizontal and isothermal heating surface—were constructed. The value of the minimum film boiling temperature $T_{p,min}$ was calculated from the criterion of equality of local potentials for two competitive transfer systems. The curves $p = p(T_{p,min})$ for hydrodynamic and thermodynamic models of the film boiling crisis for water have been determined and compared with the results achieved for the dissipative model.

1. ANALYSIS OF THE STATE OF THE ART

IN EXTENSIVE review papers [1, 2] the state of the art concerning the film boiling crisis was discussed. The following factors determining the phenomenon can be distinguished:

(a) Taylor–Helmholtz instability of the liquid–vapour interface (hydrodynamic models);
(b) excess of maximum liquid superheating temperature (thermodynamic models);
(c) spontaneous homogeneous nucleation.

In the conclusion of ref. [2] the specification of the basic physical factors composing particular models was made as well as the comparison of these models. As it results from the analysis [1, 2] the values of the minimum film boiling temperature, obtained from different models for water at atmospheric pressure, approximate each other and are contained in the scatter of experimental results.

The experiments conducted by many investigators [3–7], dealing with the influence of pressure on the value of the minimum film boiling temperature, for numerous different liquids, do not present an explicit answer which, from already known mathematical models of the film boiling crisis, approaches the experimental data best.

In this study $T_{p,min}$ is understood as the heating surface temperature at the point of minimum heat flux in stable film boiling.

Heating surface temperatures, both below and above T_{crit}, have been reported for $T_{p,min}$ at elevated pressures in the quoted literature.

The results of Emmerson and Snoek's experiments for freon C51-12, freon 113, chloroform and carbon tetrachloride provide the values of $T_{p,min} < T_{crit}$, in the whole pressure range examined [3]. Qualitatively the same results were found by Nikolayev *et al.* for n-hexane and n-pentane [4]. On the other hand Emmerson and Snoek obtained $T_{p,min} > T_{crit}$ for water at pressures $p \leqslant 15 \times 10^5$ Pa. Their results are contradictory to those of Yao and Henry [5], which were always lower than T_{crit} in the same range of pressure. The results of $T_{p,min} > T_{crit}$ were found by Bier *et al.* [6] for octafluorobutane, for a wide range of pressures. Sciance and Colver [7] determined the difference $T_{p,min} - T_{sat}$ as a function of pressure for methane, ethane, propane and butane. They also obtained some results of $T_{p,min} > T_{crit}$, at elevated pressures.

The theoretical curves of $p = p(T_{p,min})$ were calculated for water (Fig. 1) from the hypothesis discussed in refs. [1, 2], for pressures ranging from $p = 1 \times 10^5$ Pa up to its critical value. Qualitatively identical results of calculations were reached for freon

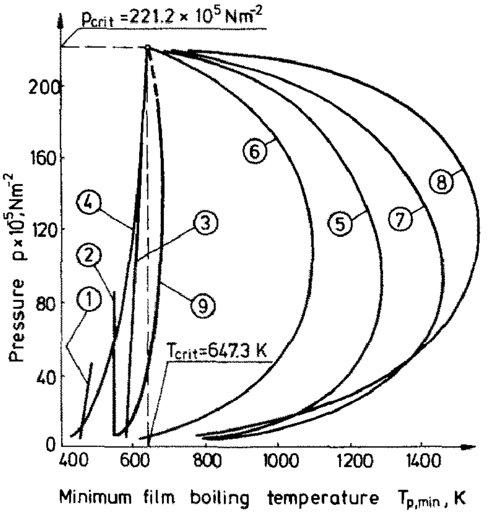

FIG. 1. Effect of pressure upon the theoretical values of $T_{p,min}$ for saturated water on a plane, horizontal and isothermal surface (or made of gold). Thermodynamic models: ①, Baumeister and Simon [14]; ②, Spiegler *et al.* [2]; ③, homogeneous nucleation [2]; ④, saturation line. Hydrodynamic models: ⑤, Henry [11]; ⑥, Berenson [1]; ⑦, Gunnerson and Cronenberg, variant II [13]; ⑧, Gunnerson and Cronenberg, variant I [12]. The dissipative model, ⑨.

NOMENCLATURE

a	thermal diffusivity [$\mathrm{m^2\,s^{-1}}$]
c_p	specific heat at constant pressure [$\mathrm{J\,kg^{-1}\,K^{-1}}$]
E^*	local potential [W]
EQ	extensive quantity
g	gravitational acceleration [$\mathrm{m\,s^{-2}}$]
h	enthalpy [$\mathrm{J\,kg^{-1}}$]
L_{ij}	kinetic coefficient
p	pressure [$\mathrm{N\,m^{-2}}$, Pa]
q	heat flux [$\mathrm{W\,m^{-2}}$]
r	coordinate [m]
R	radius of a droplet's bottom [m]
S	surface [$\mathrm{m^2}$]
t	time [s]
T	temperature [K]
u	velocity component [$\mathrm{m\,s^{-1}}$]
v	velocity [$\mathrm{m\,s^{-1}}$]
V	volume [$\mathrm{m^3}$]
w	velocity component [$\mathrm{m\,s^{-1}}$]
x	exponent
z	coordinate [m].

Greek symbols

Γ	intensive parameter (stimulus)
δ	thickness of a vapour film and a liquid boundary layer [m]
λ	conductivity [$\mathrm{W\,m^{-1}\,K^{-1}}$]
μ	dynamic viscosity [$\mathrm{N\,s\,m^{-2}}$]; chemical potential [$\mathrm{J\,kg^{-1}}$]
ρ	density [$\mathrm{kg\,m^{-3}}$]
ϕ	generalized dissipative potential [$\mathrm{W\,s^{-1}}$]†
ψ	generalized dissipative function [$\mathrm{W\,s^{-1}\,m^{-3}}$]‡
Ω	functional of evolution [W].

Subscripts

a	ambient
b	boundary
crit	critical
l	liquid
lv	phase change or interface
min	minimum
ms	maximum superheating
npc	non-equilibrium phase change
p	heating surface (plate)
r	normal to r-coordinate
surf	related to a surface
sat	saturation
v	vapour
vol	related to a volume
z	normal to z-coordinate
δ	at the limit of a boundary layer.

Superscripts

0	stationary
~	set value.

22 and ethanol in refs. [8, 9]. As it is seen from Fig. 1, thermodynamic models and the model based on the homogeneous nucleation phenomenon give values of $T_{\mathrm{p,min}}$ lower than T_{sat}, for elevated pressures. The values of $T_{\mathrm{p,min}}$ predicted by hydrodynamic models are much higher than T_{crit} for elevated pressures. Comparison of experimental values of $T_{\mathrm{p,min}}$ with theoretical ones, received from hydrodynamic models, for water (Fig. 1), ethanol [9] and for methane, ethane, propane, and butane [7] leads to the conclusion that these models overestimate $T_{\mathrm{p,min}}$, especially at elevated pressures.

According to the hydrodynamic hypotheses, for $T_{\mathrm{p}} \leqslant T_{\mathrm{p,min}}$ the loss of stability of the vapour–liquid interface takes place. In that case the amplitude of interface disturbances theoretically approaches infinity. Thus for $T_{\mathrm{p}} \leqslant T_{\mathrm{p,min}}$ saturated liquid does not undergo evaporation at a certain distance from a heating surface and the vapour film is not created at the surface. Since liquid is in direct contact with the surface it can reach the surface temperature. Skripov and Pavlov claim (in ref. [10]) that considerable superheatings of liquid can be obtained. The maximum temperature, which they obtained experimentally for water was $T_{\mathrm{ms}} = 575.2$ K at $p = 1.013 \times 10^5$ Pa, whereas Briggs managed to keep, for 5 s, the temperature $T_{\mathrm{ms}} = 540$ K (in ref. [10]). Nevertheless it is impossible to reach superheatings higher than T_{crit}, as it would result from hydrodynamic models (Fig. 1).

A different definition of $T_{\mathrm{p,min}}$ [1–3, 5, 7, 11–14] seems to be the essential cause of discrepancies among the experimental results, beside measurement errors.

Therefore, it is necessary to establish a proper physical model not only of the film boiling crisis at elevated pressures, but first of all the models of transition and film boiling under these conditions.

2. CONCEPTION OF VAPOUR MICROLAYER IN TRANSITION BOILING

Experimental results and theoretical considerations related to the assumption that in transition boiling the liquid which contacts a heating surface can receive superheating higher than T_{crit} (what is not physical) or that a vapour microlayer in transition boiling is formed at a heating surface. This microlayer would first of all fill the micropores in a heating surface and its thickness should be much smaller than a vapour

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† The name of the function ϕ is proposed by the author.

‡ The name of the function ψ was proposed by the Editor of the Russian translation of ref. [17].

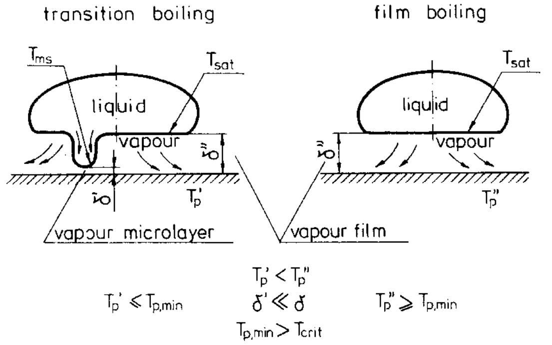

FIG. 2. The concept of vapour microlayer in transition boiling—hypothesis.

film thickness. The microlayer thickness would be defined by the position of an isotherm of the maximum possible liquid superheating, T_{ms}, for certain pressures. Heat and mass would be transferred through the microlayer only by diffusion because of a small characteristic linear dimension and a small Rayleigh number. Figure 2 illustrates this hypothesis. It is necessary to emphasize that this microlayer would be unstable and it would convert into a vapour film or a liquid boundary layer depending on the direction of the heating surface temperature changes. The hypothesis of the vapour microlayer would make the hydrodynamic models correct, in a qualitative sense, for elevated pressures, since they give $T_{p,min} > T_{crit}$ (Fig. 1). The hypothesis might find its application in the dissipative model of the film boiling crisis which is the essence of the presented theoretical considerations.

3. COMMENTS ON THE VARIATIONAL HYPOTHESIS OF PHASE CHANGE

In ref. [15] it was assumed that the dissipative features of the examined thermodynamic system decide on the processes taking place in it, e.g. phase change. Local potential E^* (Γ, Γ^0), formulated by Glansdorf and Prigogine [16] was used for characterizing these features and applied by Schechter [17] to describe the phenomena of heat and mass transfer. The condition $L_{ij}(\Gamma) \approx L_{ij}(\Gamma^0)$ [16, 17] assumed in defining local potential, means that the examined system may be in a state of little deviation from a stationary one and will evolve to this state. For a certain distribution of intensive parameters this evolution may realize itself in a monotonous relaxation process to a stationary state. For another one it may lead to a phase change (e.g. liquid–vapour) or to a change of transfer system (e.g. appearance or disappearance of natural convection). The aim of the hypothesis formulated in ref. [15] regarding the non-equilibrium phase change, understood as a classical one or as an alternation of the way of transfer of *EQ*, is defining the criterion for determining the boundary conditions under which these phase changes may take place. The open, monophase thermodynamic system is called the transfer system. A physical model adequate to this concept contains two kinds of independent parameters. The first one describes the static features of the system, i.e. the features of the phase, whereas the second one describes the dynamic features, i.e. the way of transfer of *EQ*. The phase of the transfer system can be specified explicitly on the basis of the features already known, e.g. density, but the way of transfer of *EQ* realized in it is not given explicitly by the form of the dissipative function [18]. If in the process of evolution two transfer systems become equivalent in a sense of energy dissipation for the same boundary values of intensive parameters, then according to the presented reasoning it may come to a stepwise phase change or to the same change of transfer systems of *EQ*. It is equivalent, in a qualitative sense, to the loss of stability in both of the competitive transfer systems.

This phenomenon was defined as the non-equilibrium phase change [15]. The physical meaning and the way of determining the generalized dissipative function ψ and the potential ϕ and also the local potential E^* has been given in refs. [16, 17].

For describing the qualities of dissipative thermodynamic systems, the following functional of evolution was assumed:

$$\Omega = \int_0^\infty \phi \, \mathrm{d}t = \int_0^\infty \left(\frac{\partial}{\partial t} E^*\right) \mathrm{d}t$$

$$= E^*(\Gamma^0, \Gamma^0)\Big|_{t \to \infty} - E^*(\Gamma^0, \Gamma)\Big|_{t=0} \leqslant 0 \quad (1)$$

together with the hypothesis saying that the real transfer processes in an examined system proceed in such a way, that Ω calculated along the trajectory of evolution to a stationary state has the minimum value in comparison to the values which Ω may have along the variational trajectories. Departure from this rule appears only in the region where the competitive transfer systems are within the reach of small fluctuations of the intensive parameters (stimuli).

For certain distributions of the intensive parameters (T^0, v^0, p^0 or μ^0), characteristic for each competitive transfer system, it comes to the non-equilibrium phase change:

$$\Omega^{\mathrm{I}}\Big|_{\Gamma_b = \Gamma^0_{b,npc}} = \Omega^{\mathrm{II}}\Big|_{\Gamma_b = \Gamma^0_{b,npc}} . \quad (2)$$

This condition enables us to determine the set of boundary values $\Gamma^0_{b,npc}$, for which the mutual take over of the control of dissipation by the competitive transfer system occurs. In the examined region $\Gamma^0_{b,npc} \pm \delta\Gamma$ the relation $\partial E^*/\partial t < 0$, based on the stationary solution of the conservation equations, loses its validity, because the solution can become unstable [16].

For time independent boundary conditions the local potential is a result of the variational principle constructed in such a manner that it brings a non-stationary solution to the stationary form [16, 17]. Each non-stationary solution is thus 'parametered' by the stationary state Γ^0 due to the averaged kinetic coefficients $L_{ij}(\Gamma^0)$.

It was later assumed that the evolution of the thermodynamic systems containing or limited by an interface, proceeds in such a way that the rate of displacement of this surface is lower than the corresponding rate of the intensive parameter change in both phases. It allows to approximate the evolution of such a system through the consecutive, one close to each other, quasi-stationary states and describes them by local potential. The following reasoning was then carried out. Two non-stationary, temporarily coexisting transfer systems of EQ, minimally deviated from their stationary states are considered. The deviation is the effect of small identical disturbances of intensive parameters in both of them. The situation when liquid 'tongues' occasionally penetrate the vapour film at T_p close to $T_{p,min}$ could be the proper examples for that (see Fig. 15 in ref. [19]). Then at any moment in time the following can be expected:

$$ {}^{\mathrm{I}}E^*\Big|_{t=t_0} = {}^{\mathrm{II}}E^*\Big|_{t=t_0} . \qquad (3)$$

The state $t = t_0$ can be regarded as the beginning of the observation of the transfer systems of EQ, evolving to their stationary states. Assuming that these coexisting transfer systems can realize themselves in the states close to the common stationary one then the following is true:

$$ {}^{\mathrm{I}}E^*\Big|_{t\to\infty} = {}^{\mathrm{II}}E^*\Big|_{t\to\infty} . \qquad (4)$$

This corresponds, for instance, to the possibility of having both nucleate and film boiling regimes on the same electrically heated wire simultaneously as it was observed by van Stralen, Reiman and Grigull (in ref. [10]).

Equation (4) physically means that for certain boundary conditions either system I or system II equally control the dissipative processes connected with the transfer of mass, momentum and energy. The systems in which equation (3) or equation (4) are fulfilled, fulfil also criterion (2).

It was demonstrated in ref. [15] that criterion (2) is not contradictory to the criterion of phase change for equilibrium systems.

The presented consideration about competitive transfer systems are based on those of Glansdorf and Prigogine, related to coexisting 'thermodynamic branches' in the Bénard phenomenon [16].

4. DISSIPATIVE MODEL OF FILM BOILING CRISIS

The hypothesis of non-equilibrium phase change was applied to describe the nucleate boiling crisis [20, 21] and to analyse instability of a low pressure thermionic generator [22]. Application of this hypothesis to modelling film boiling crisis was preceded by the experimental investigations [19]. The results of these investigations allow one to say that for the film boiling crisis such phenomena are observed which can be interpreted as the processes of self-acting comparison of energy dissipation (generalized entropy production) in two competitive transfer systems [15].

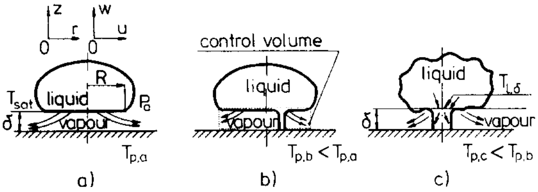

FIG. 3. Graphical illustration of film boiling crisis for a liquid droplet on a plane horizontal heating surface. (a) Stable film boiling, $T_{p,a} \gg T_{p,min}$. (b) Film boiling, $T_{p,b} < T_{p,a}$ and $T_{p,b} \geqslant T_{p,min}$. The 'tongues' of liquid wet the heating surface but do not destroy the vapour film. (c) Transition boiling, $T_{p,c} < T_{p,b}$ and $T_{p,c} \leqslant T_{p,min}$. The vapour film loses its stability and liquid tends to keep contact with the heating surface. Both (a) and (c) refer to two competitive transfer systems connected with vapour film and liquid boundary layer, respectively [19].

Together with decreasing heating surface temperature from the temperature characteristic for film boiling to transition boiling, incidental contacts between the liquid and the heating surface occur [5, 19]. Duration, surface of contact and frequency increase with a drop in surface temperature. The whole phenomenon is of stochastic character. If T_p decreases below some limiting value—$T_{p,min}$—vapour film begins to vanish and the particles of liquid replace the vapour particles (Fig. 3). According to the variational hypothesis, with the change of boiling regime: film boiling → transition boiling, the 'tongues' of liquid penetrating through the vapour film will not decay if dissipation of energy in 'tongues' is equal to energy dissipation in the vapour, in the same volume.

The first competitive transfer system is connected with vapour (vapour film), the second system with a liquid phase (liquid boundary layer). The minimum film boiling temperature—$T_{p,min}$—was defined as the heating surface temperature at which the liquid or vapour phase, being in contact with the surface, will dissipate the same amount of energy in the same control volume. It demands that criterion (3) or (4) is fulfilled, from which the quested value of $T_{p,min}$ is calculated. It is possible when the real ways of mass, momentum and energy transfer are known in both transfer systems. The drop in surface temperature below $T_{p,min}$ will result in taking over of the control of dissipation by the transfer system connected with liquid, i.e. in the breakdown of the stable vapour film.

On the basis of the analysis made in ref. [23], it was assumed for the presented considerations, that the convection in vapour film can be described using the combination of stagnation and creeping flows [24]. Tien assumed, for determining Nusselt number characteristic for nucleate boiling on a plane heating surface, that heat transfer in the boundary layer is controlled by a liquid phase for which the model of stagnation flow should be used. He achieved a good agreement with the experimental results of Yamagata and others, Gaertner and Westwater (in ref. [10]).

The experimental [19] and theoretical evidence for the dissipative model of the film boiling crisis were earlier presented briefly in ref. [25].

In the considered problem of the film boiling crisis of a liquid droplet the following competitive transfer systems were assumed (Fig. 3):

(I) vapour film + stagnation and creeping flows (film boiling regime [23, 24]);

(II) liquid boundary layer + stagnation and creeping flows (approximated model of flow in a liquid layer 'trying to replace' the vapour film–transition boiling regime).

In agreement with the hypothesis of non-equilibrium phase change it was assumed that both phases can occur, i.e. liquid and vapour at the same temperature and pressure beyond the saturation line. It was also assumed that, as it is demanded by the definition of local potential, the metastable states do not deviate much from the stationary ones.

The local potentials for the vapour and liquid phases were defined under the following boundary conditions:

(a) constant temperature of the heating surface, T_p;

(b) constant temperature at the boundary of the vapour film (vapour–liquid interface) equal to the saturation temperature, T_{sat};

(c) constant temperature at the limit of the liquid boundary layer equal to the temperature determined from the ratio of heat fluxes, received from the heating surface by vapour and liquid, $T_{l,\delta}$;

(d) the identical pressure for both phases, which were determined on the basis of static-force balance at the upper boundary of the control volume being equal to the vapour film volume, Fig. 3 [23, 24].

5. CONSTRUCTION OF LOCAL POTENTIAL

The conservation equations for an incompressible fluid and an axisymmetrical flow are as follows:

$$\frac{1}{r}\frac{\partial(ru)}{\partial r}+\frac{\partial w}{\partial z}=0$$

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial r}+w\frac{\partial u}{\partial z}\right)=-\frac{\partial p}{\partial r}+\mu\left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}(ru)\right)+\frac{\partial^2 u}{\partial z^2}\right]$$

$$\rho\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial r}+w\frac{\partial w}{\partial z}\right)=-\frac{\partial p}{\partial z}+\mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial w}{\partial r}\right)+\frac{\partial^2 w}{\partial z^2}\right]$$

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial r}+w\frac{\partial T}{\partial z}=a\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)+\frac{\partial^2 T}{\partial z^2}\right]. \quad (5)$$

According to the model, combining stagnation and creeping flows, inertial terms in momentum equations (5) were neglected in both phases and the following simplifications were assumed [23, 24]:

$$u\frac{\partial T}{\partial r}\ll w\frac{\partial T}{\partial z}$$
$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)\ll\frac{\partial^2 T}{\partial z^2}. \quad (6)$$

Equations (5) are now written as

$$0=\frac{1}{r}\frac{\partial(ru)}{\partial r}+\frac{\partial w}{\partial z}$$
$$\rho\frac{\partial u}{\partial t}=-\frac{\partial p}{\partial r}+\mu\left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}(ru)\right)+\frac{\partial^2 u}{\partial z^2}\right]$$
$$\rho\frac{\partial w}{\partial t}=-\frac{\partial p}{\partial z}+\mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial w}{\partial r}\right)+\frac{\partial^2 w}{\partial z^2}\right] \quad (7)$$
$$\frac{\partial T}{\partial t}=-w\frac{\partial T}{\partial z}+a\frac{\partial^2 T}{\partial z^2}.$$

One of the numerous possible forms of a generalized dissipative function ψ [17] is obtained by multiplying in succession equations (7) by $\partial p/\partial t$, $\partial u/\partial t$, $\partial w/\partial t$ and $\rho c_p \tilde{T}_p^{-1}\,\partial T/\partial t$, and then adding them. When forming the function ψ, its fundamental quality is used [16, 17]

$$\psi=\left[\rho\left(\frac{\partial u}{\partial t}\right)^2+\rho\left(\frac{\partial w}{\partial t}\right)^2+\frac{\rho c_p}{\tilde{T}_p}\left(\frac{\partial T}{\partial t}\right)^2\right]\leqslant 0 \quad (8)$$

and therefore

$$\psi=\frac{1}{r}\frac{\partial p}{\partial t}\frac{\partial(ru)}{\partial r}+\frac{\partial p}{\partial t}\frac{\partial w}{\partial z}+\frac{\partial u}{\partial t}\frac{\partial p}{\partial r}$$
$$-\mu\frac{\partial u}{\partial t}\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}(ru)\right)-\mu\frac{\partial u}{\partial t}\frac{\partial^2 u}{\partial z^2}$$
$$+\frac{\partial w}{\partial t}\frac{\partial p}{\partial z}-\mu\frac{\partial w}{\partial t}\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial w}{\partial r}\right)\right]-\mu\frac{\partial w}{\partial t}\frac{\partial^2 w}{\partial z^2}$$
$$+\frac{\rho c_p}{\tilde{T}_p}\frac{\partial T}{\partial t}w\frac{\partial T}{\partial z}-\frac{a\rho c_p}{\tilde{T}_p}\frac{\partial T}{\partial t}\frac{\partial^2 T}{\partial z^2}\leqslant 0. \quad (9)$$

Integrating equation (9) over a volume, the expression for the generalized dissipative potential ϕ is obtained

$$\phi=\int_V \psi\,\mathrm{d}V. \quad (10)$$

Next, some terms of the potential ϕ are transformed to extract the divergent terms and divide the volume integral (10) into two parts, i.e. the integral over volume V and the integral over surface S, limiting this volume

$$
\begin{aligned}
&\frac{\partial p}{\partial t}\frac{1}{r}\frac{\partial(ru)}{\partial r}+\frac{\partial u}{\partial t}\frac{\partial p}{\partial r}=\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{\partial}{\partial t}p(ru)\right)\\
&\qquad -u\frac{\partial}{\partial t}\left(\frac{\partial p}{\partial r}\right)-p\frac{\partial}{\partial t}\left(\frac{1}{r}\frac{\partial(ur)}{\partial r}\right)\\
&\frac{\partial p}{\partial t}\frac{\partial w}{\partial z}+\frac{\partial w}{\partial t}\frac{\partial p}{\partial z}=\frac{\partial}{\partial z}\left(\frac{\partial(pw)}{\partial t}\right)\\
&\qquad -w\frac{\partial}{\partial t}\left(\frac{\partial p}{\partial z}\right)-p\frac{\partial}{\partial t}\left(\frac{\partial w}{\partial z}\right)\\
&-\mu\frac{\partial u}{\partial t}\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial(ru)}{\partial r}\right)=-\frac{\mu}{r}\frac{\partial}{\partial r}\left(\frac{\partial u}{\partial t}\frac{\partial(ru)}{\partial r}\right)\\
&\qquad +\frac{\mu}{2}\frac{\partial}{\partial t}\left(\frac{1}{r}\frac{\partial(ru)}{\partial r}\right)^2\\
&-\mu\frac{\partial w}{\partial t}\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial w}{\partial r}\right)\right]=-\frac{\mu}{r}\frac{\partial}{\partial r}\left[\frac{\partial w}{\partial t}\left(r\frac{\partial w}{\partial r}\right)\right]\\
&\qquad +\frac{\mu}{2}\frac{\partial}{\partial t}\left(\frac{\partial w}{\partial r}\right)^2\\
&-\mu\frac{\partial u}{\partial t}\frac{\partial^2 u}{\partial z^2}=-\mu\frac{\partial}{\partial z}\left(\frac{\partial u}{\partial t}\frac{\partial u}{\partial z}\right)+\frac{\mu}{2}\frac{\partial}{\partial t}\left(\frac{\partial u}{\partial z}\right)^2\\
&-\mu\frac{\partial w}{\partial t}\frac{\partial^2 w}{\partial z^2}=-\mu\frac{\partial}{\partial z}\left(\frac{\partial w}{\partial t}\frac{\partial w}{\partial z}\right)+\frac{\mu}{2}\frac{\partial}{\partial t}\left(\frac{\partial w}{\partial z}\right)^2\\
&-\frac{a\rho c_p}{\tilde{T}_{\mathrm{p}}}\frac{\partial T}{\partial t}\frac{\partial^2 T}{\partial z^2}=-\frac{\lambda}{\tilde{T}_{\mathrm{p}}}\frac{\partial}{\partial z}\left(\frac{\partial T}{\partial t}\frac{\partial T}{\partial z}\right)+\frac{\lambda}{2\tilde{T}_{\mathrm{p}}}\frac{\partial}{\partial t}\left(\frac{\partial T}{\partial z}\right)^2.
\end{aligned}
\tag{11}
$$

Introducing transformations (11) in integral (10) results in

$$
\begin{aligned}
\phi=\int_V&\left\{\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{\partial}{\partial t}p(ru)\right)-u\frac{\partial}{\partial t}\left(\frac{\partial p}{\partial r}\right)\right.\\
&-p\frac{\partial}{\partial t}\left(\frac{1}{r}\frac{\partial(ur)}{\partial r}\right)+\frac{\partial}{\partial z}\left(\frac{\partial}{\partial t}(pw)\right)\\
&-w\frac{\partial}{\partial t}\left(\frac{\partial p}{\partial z}\right)-p\frac{\partial}{\partial t}\left(\frac{\partial w}{\partial z}\right)-\frac{\mu}{r}\frac{\partial}{\partial r}\left(\frac{\partial u}{\partial t}\frac{\partial(ru)}{\partial r}\right)\\
&+\frac{\mu}{2}\frac{\partial}{\partial t}\left(\frac{1}{r}\frac{\partial(ru)}{\partial r}\right)^2-\frac{\mu}{r}\frac{\partial}{\partial r}\left[\frac{\partial w}{\partial t}\left(r\frac{\partial w}{\partial r}\right)\right]\\
&+\frac{\mu}{2}\frac{\partial}{\partial t}\left(\frac{\partial w}{\partial r}\right)^2-\mu\frac{\partial}{\partial z}\left(\frac{\partial u}{\partial t}\frac{\partial u}{\partial z}\right)+\frac{\mu}{2}\frac{\partial}{\partial t}\left(\frac{\partial u}{\partial z}\right)^2\\
&-\mu\frac{\partial}{\partial z}\left(\frac{\partial w}{\partial t}\frac{\partial w}{\partial z}\right)+\frac{\mu}{2}\frac{\partial}{\partial t}\left(\frac{\partial w}{\partial z}\right)^2+\frac{\rho c_p}{\tilde{T}_{\mathrm{p}}}w\frac{\partial T}{\partial z}\frac{\partial T}{\partial t}\\
&\left.-\frac{\lambda}{\tilde{T}_{\mathrm{p}}}\frac{\partial}{\partial z}\left(\frac{\partial T}{\partial t}\frac{\partial T}{\partial z}\right)+\frac{\lambda}{2\tilde{T}_{\mathrm{p}}}\frac{\partial}{\partial t}\left(\frac{\partial T}{\partial z}\right)^2\right\}\mathrm{d}V.
\end{aligned}
\tag{12}
$$

According to the Gauss–Green–Ostrogradzki theorem from integral (12) the following is obtained:

$$
\begin{aligned}
\phi=\int_{S_r}&\left\{\frac{1}{r}\frac{\partial}{\partial t}[p(ru)]-\frac{\mu}{r}\frac{\partial u}{\partial r}\frac{\partial(ru)}{\partial r}\right.\\
&\left.-\mu\frac{\partial w}{\partial t}\frac{\partial w}{\partial r}\right\}\mathrm{d}S_r+\int_{S_z}\left\{\frac{\partial}{\partial t}(pw)-\mu\frac{\partial u}{\partial t}\frac{\partial u}{\partial z}\right.\\
&\left.-\mu\frac{\partial w}{\partial t}\frac{\partial w}{\partial z}-\frac{\lambda}{\tilde{T}_{\mathrm{p}}}\frac{\partial T}{\partial t}\frac{\partial T}{\partial z}\right\}\mathrm{d}S_z+\int_V\left\{-u\frac{\partial}{\partial t}\left(\frac{\partial p}{\partial r}\right)\right.\\
&-p\frac{\partial}{\partial t}\left(\frac{1}{r}\frac{\partial(ru)}{\partial r}\right)-w\frac{\partial}{\partial t}\left(\frac{\partial p}{\partial z}\right)-p\frac{\partial}{\partial t}\left(\frac{\partial w}{\partial z}\right)\\
&+\frac{\mu}{2}\frac{\partial}{\partial t}\left(\frac{1}{r}\frac{\partial(ru)}{\partial r}\right)^2+\frac{\mu}{2}\frac{\partial}{\partial t}\left(\frac{\partial w}{\partial r}\right)^2\\
&+\frac{\mu}{2}\frac{\partial}{\partial t}\left(\frac{\partial u}{\partial z}\right)^2+\frac{\mu}{2}\frac{\partial}{\partial t}\left(\frac{\partial w}{\partial z}\right)^2+\frac{\rho c_p}{\tilde{T}_{\mathrm{p}}}w\frac{\partial T}{\partial z}\frac{\partial T}{\partial t}\\
&\left.+\frac{\lambda}{2\tilde{T}_{\mathrm{p}}}\frac{\partial}{\partial t}\left(\frac{\partial T}{\partial z}\right)^2\right\}\mathrm{d}V.
\end{aligned}
\tag{13}
$$

For the flow in the vapour film under a droplet and in the liquid boundary layer it was assumed that pressures and temperatures at the boundaries of the control volume are constant for a given phase, and therefore

$$
\begin{gathered}
\frac{1}{r}\frac{\partial}{\partial t}[p(ru)]=\frac{1}{r}\tilde{p}\frac{\partial}{\partial t}(ru)\\
\frac{\partial(pw)}{\partial t}=\tilde{p}\frac{\partial w}{\partial t}\\
\frac{\lambda}{\tilde{T}_{\mathrm{p}}}\frac{\partial T}{\partial t}\frac{\partial T}{\partial z}=0.
\end{gathered}
\tag{14}
$$

With regard to equation (14) the detailed form of the potential ϕ, for axisymmetrical and cylindrical control volume (Fig. 3) is as follows:

$$
\mathrm{d}S_r=2\pi R\,\mathrm{d}z,\quad \mathrm{d}S_z=2\pi r\,\mathrm{d}r,\quad \mathrm{d}V=2\pi r\,\mathrm{d}r\,\mathrm{d}z
$$

$$
\begin{aligned}
\phi=2\pi&\int_0^{\delta}\tilde{p}(R,z)\frac{\partial}{\partial t}(ru)\bigg|_{r=R}\mathrm{d}z-2\pi\mu\\
&\times\int_0^{\delta}\frac{\partial u}{\partial t}\frac{\partial(ru)}{\partial r}\bigg|_{r=R}\mathrm{d}z-2\pi R\mu\int_0^{\delta}\frac{\partial w}{\partial t}\frac{\partial w}{\partial r}\bigg|_{r=R}\mathrm{d}z\\
&+2\pi\int_0^{R}\tilde{p}(r,\delta)\frac{\partial w}{\partial t}\bigg|_{z=\delta}r\,\mathrm{d}r-2\pi\mu\\
&\times\int_0^{R}\frac{\partial u}{\partial t}\frac{\partial u}{\partial z}\bigg|_{z=\delta}r\,\mathrm{d}r-2\pi\mu\int_0^{R}\frac{\partial w}{\partial t}\frac{\partial w}{\partial z}\bigg|_{z=\delta}r\,\mathrm{d}r\\
&+2\pi\int_0^{R}\int_0^{\delta}\left\{-u\frac{\partial}{\partial t}\left(\frac{\partial p}{\partial r}\right)-p\frac{\partial}{\partial t}\left(\frac{1}{r}\frac{\partial(ur)}{\partial r}\right)\right.\\
&-w\frac{\partial}{\partial t}\left(\frac{\partial p}{\partial z}\right)-p\frac{\partial}{\partial t}\left(\frac{\partial w}{\partial z}\right)+\frac{\mu}{2}\frac{\partial}{\partial t}\left(\frac{1}{r}\frac{\partial(ru)}{\partial r}\right)^2\\
&+\frac{\mu}{2}\frac{\partial}{\partial t}\left(\frac{\partial w}{\partial r}\right)^2+\frac{\mu}{2}\frac{\partial}{\partial t}\left(\frac{\partial u}{\partial z}\right)^2+\frac{\mu}{2}\frac{\partial}{\partial t}\left(\frac{\partial w}{\partial z}\right)^2\\
&\left.+\frac{\rho c_p}{\tilde{T}_{\mathrm{p}}}w\frac{\partial T}{\partial t}\frac{\partial T}{\partial z}+\frac{\lambda}{2\tilde{T}_{\mathrm{p}}}\frac{\partial}{\partial t}\left(\frac{\partial T}{\partial z}\right)^2\right\}r\,\mathrm{d}r\,\mathrm{d}z.
\end{aligned}
\tag{15}
$$

In agreement with the definition of local potential E^* [16, 17] and the detailed form of the potential ϕ (15) one obtains

$$\phi = \frac{\partial E^*}{\partial t} = \frac{\partial}{\partial t}(E^*_{\mathrm{vol}} + E^*_{\mathrm{surf}}) \tag{16}$$

$$\begin{aligned} E^*_{\mathrm{vol}} = 2\pi \int_0^R \int_0^\delta \Big\{ & -u^0 \frac{\partial p}{\partial r} - \frac{p^0}{r}\frac{\partial (ur)}{\partial r} - w^0 \frac{\partial p}{\partial z} \\ & - p^0 \frac{\partial w}{\partial z} + \frac{\mu}{2}\left[\left(\frac{1}{r}\frac{\partial (ru)}{\partial r}\right)^2 + \left(\frac{\partial u}{\partial z}\right)^2 \right. \\ & \left. + \left(\frac{\partial w}{\partial z}\right)^2\right] + \frac{\rho c_p}{\tilde{T}_{\mathrm{p}}} w^0 \frac{\partial T^0}{\partial z} T \\ & + \frac{\lambda}{2\tilde{T}_{\mathrm{p}}}\left(\frac{\partial T}{\partial z}\right)^2 \Big\} r\,\mathrm{d}r\,\mathrm{d}z \end{aligned}$$

$$\begin{aligned} E^*_{\mathrm{surf}} = 2\pi R \int_0^\delta & \tilde{p}(R,z) u(R,z)\,\mathrm{d}z \\ & - 2\pi\mu \int_0^\delta u(R,z) \left.\frac{\partial (ru)^0}{\partial r}\right|_{r=R} \mathrm{d}z \\ & + 2\pi \int_0^R \tilde{p}(r,\delta) w(r,\delta) r\,\mathrm{d}r. \end{aligned} \tag{17}$$

In integrals (17) the relations given below were used, true for combination of stagnation and creeping flows [23, 24] (Fig. 3):

$$\begin{aligned} & \frac{\partial w}{\partial r} = 0, \quad u(r,\delta) = 0 \\ & \left.\frac{\partial w}{\partial z}\right|_{z=\delta} = 0. \end{aligned} \tag{18}$$

6. REMARKS ON THE MODEL OF CONVECTION IN THE VAPOUR FILM UNDER A DROPLET AND IN THE LIQUID BOUNDARY LAYER

In ref. [17] the numerical solution of stationary conservation equations, for the convection in a vapour film under a droplet in film boiling was presented. It was shown that the analytical solution of Baumeister and Hamill [24], based on the combination of stagnation and creeping flows, is a good approximation of the solution of a more accurate model.

The pressure and the velocities in radial and normal direction to a heating surface were determined from analytical relations of Baumeister and Hamill [24]. For calculating the thickness of the vapour film and the temperature distribution they employed the analytical approximation, which is not true for liquid and vapour at elevated pressures. The energy equation (5), after taking into account the simplifying assumptions (6), was integrated numerically for determining the temperature distribution as well as a vapour film thickness.

It is particularly difficult to determine the temperature of superheated liquid at the limit of the liquid boundary layer. The effect of wetting a heating surface by the 'tongues' of liquid penetrating through the vapour film was taken into consideration, in many different ways, by Henry [11], Gunnerson and Cronenberg [12, 13], Baumeister and Simon [14] in their models of the film boiling crisis. Henry [11] assumed that if the layer of boiling liquid adheres to the heating surface, then its cooling down is a function of the following ratio:

$$\frac{h_{\mathrm{lv}}}{c_{p,\mathrm{p}}(T_{\mathrm{p,min}} - T_{\mathrm{sat}})}. \tag{19}$$

According to Henry's way of reasoning, cooling down of the same heating surface induced by vapour film adhesion will be a function of the ratio

$$\frac{c_{p,\mathrm{v}}(T_{\mathrm{p,min}} - T_{\mathrm{sat}})}{c_{p,\mathrm{p}}(T_{\mathrm{p,min}} - T_{\mathrm{sat}})}. \tag{20}$$

Therefore, the ratio of heat fluxes taken from the heating surface by liquid and vapour will be described by the relationship

$$\frac{q_{\mathrm{l}}}{q_{\mathrm{v}}} = \left(\frac{h_{\mathrm{lv}}}{c_{p,\mathrm{v}}(T_{\mathrm{p,min}} - T_{\mathrm{sat}})}\right)^x \tag{21}$$

where

$$q_{\mathrm{v}} = \lambda_{\mathrm{v}} \left.\frac{\partial T_{\mathrm{v}}}{\partial z}\right|_{z=0}, \quad q_{\mathrm{l}} = \lambda_{\mathrm{l}} \left.\frac{\partial T_{\mathrm{l}}}{\partial z}\right|_{z=0}$$

$$x = 0.66 \text{ (constant in this study).}$$

Correlating experimental data, Henry included relation (19) with the exponent $x = 0.6$ into his own formula for minimum film boiling temperature. The value of exponent x in expression (21) is matched in such a manner that the calculated value of $T_{\mathrm{p,min}}$ for water under $p = 1 \times 10^5$ Pa should find itself in the centre of scatter of Yao and Henry's experimental data [5] as well as the data collected by Poniewski and Staniszewski [1, 2], and Żyszkowski [26]. From relations (21) the temperature of liquid at the limit of boundary layer, $T_{\mathrm{l},\delta}$, is determined.

The analytical stationary solution of momentum equations (7) [24] and the numerical solution of the energy equation for vapour are obtained under the following boundary conditions (Fig. 3):

$$\begin{array}{ll} z = 0 & u_{\mathrm{v}} = w_{\mathrm{v}} = 0, T_{\mathrm{v}} = T_{\mathrm{p}} \\ z = \delta \text{ (unknown)} & u_{\mathrm{v}} = \partial w_{\mathrm{v}}/\partial z = 0, T_{\mathrm{v}} = T_{\mathrm{sat}} \\ r = 0 & u_{\mathrm{v}} = 0 \\ r = R \text{ and } \begin{cases} z = 0 \\ z = \delta \end{cases} & p(r,z) = p_{\mathrm{a}} \end{array} \tag{22}$$

where the vapour film thickness is determined from the condition

$$\lambda_v \frac{\partial T_v}{\partial z}\bigg|_{z=\delta} = w_{v,\delta}\rho_v h_{lv}. \tag{23}$$

The condition of pressure balance on the interface (the droplet's bottom) is

$$\int_0^R p(r,\delta)2\pi r\,\mathrm{d}r = V\rho_l g + \pi R^2 p_a. \tag{24}$$

For the vapour film both the thickness δ and the velocity $w_{v,\delta}$ are determined from the solution of equations (7) with boundary conditions (22)–(24). The thickness of the liquid boundary layer in accordance with the accepted models of competitive transfer systems is known and equal to the thickness of vapour film. For the liquid boundary layer the following boundary conditions are assumed:

$z = 0$ $\quad u_l = w_l = 0, T_l = T_p$

$z = \delta$ (known) $\quad u_l = \partial w_l/\partial z = 0, T_l = T_{l,\delta}$

$r = 0$ $\quad u_l = 0$

$$r = R \text{ and } \begin{cases} z = 0 \\ z = \delta \end{cases} \quad p(r,z) = p_a$$

$$\int_0^R p(r,\delta)2\pi r\,\mathrm{d}r = V\rho_l g + \pi R^2 p_a. \tag{25}$$

The thermal properties of the superheated liquid and the superheated vapour are evaluated at the saturation and the film temperature (arithmetic mean between the heating surface and the saturation temperature) [27, 28].

7. NUMERICAL PROCEDURE

The analytical stationary solution of the equations of motion (7) for the vapour film and for the liquid boundary layer are of the same form and differ from each other only in thermal properties. The stationary temperature distributions in both boundary layers of vapour and liquid were calculated numerically with the use of library subroutines realizing the Gauss–Laguerre quadrature method (the subroutines DQG32 and DQG24 [29]). The vapour film thickness δ was determined from the non-linear equation (23) which was solved using subroutine T4EGAC [30]. This subroutine realizes Mueller's iteration scheme consisting of successive bisection and inverse parabolic interpolation. According to the accepted model of the film boiling crisis the temperature of a heating surface was searched, for which

$$E_v^*\Big|_{T_p = T_{p,\min}} = E_l^*\Big|_{T_p = T_{p,\min}} \tag{26}$$

was true. For $T_p = T_{p,\min}$ the densities of the probability of occurrence of two competitive transfer systems are equal [15], i.e. both of them can be unstable (Fig. 15 in ref. [19]) with respect to fluctuation of the boundary conditions. It means that at any moment each transfer system can be replaced by the competitive one, both situations being equally probable.

In order to calculate $T_{p,\min}$ the function POLOK was formulated

$$\mathrm{POLOK} = E_v^* - E_l^*. \tag{27}$$

Zero of the function POLOK was found by applying the subroutine DRTMI [29], which serves the same purpose as the subroutine T4EGAC [30]. The application of various library subroutines for integration and solving non-linear equations resulted only from the inability of FORTRAN to recur the subroutines of the same name.

8. RESULTS OF CALCULATIONS

The shapes of two different droplets, which were taken for numerical calculations were determined on the basis of the report [24] for $V_1 = 1 \times 10^{-6}$ m^3 and on the basis of the investigations in ref. [23] for $V_2 = 0.432 \times 10^{-7}$ m^3. This shape undergoes the change together with the film boiling pressure. Baumeister *et al.* [31] determined, in an approximate way, the dependence of the radius of a droplet's bottom (the droplet treated as a cylinder) as the function of a droplet's volume. In ref. [23] it was shown, that the correct approximation of the droplet's shape, with the assumption of the plane shape of its bottom, is not sufficient for gaining the correct instantaneous values of a droplet's volume as a function of the time of evaporation. As it is proved in the calculations, the droplet's size and also its geometry do not have any essential influence on the numerical results, i.e. the value of $T_{p,\min}$. So for determining the curve $p = p(T_{p,\min})$, Figs. 1 and 4, constant volume and radius of a droplet's bottom were assumed, as for $p = 1 \times 10^5$ Pa. It means, that the pressure difference between the bottom of a droplet and the surroundings was changing only as a function of the density of the water layer. The calculations of $T_{p,\min}$ were done for the pressure ranging from 0.2×10^5 Pa up to 195×10^5 Pa. The upper bound for the pressure arises from limitation of data in the library routine for determining the thermal properties of water [27, 28]. The numerical results from the dissipative model make qualitative approach to the results gained from hydrodynamic ones (Fig. 1). From both kinds of models the curves $p = p(T_{p,\min})$ are determined, where at elevated pressures the values $T_{p,\min} > T_{\mathrm{crit}}$ are gained. These results are nonphysical, as they would make it possible for instantaneous liquid superheatings, where $T_{ms} > T_{\mathrm{crit}}$, to occur. In light of the previously discussed experimental data [3, 6, 7], the results of calculations presented on Fig. 1 impel one to accept the

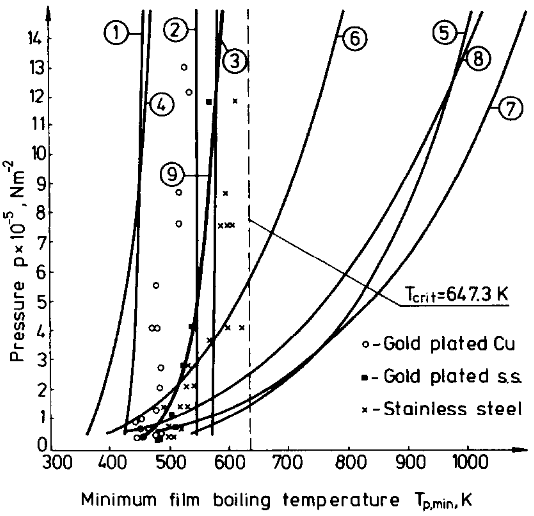

FIG. 4. Comparison of theoretical values of $T_{p,min}$ with the experimental results of Yao and Henry for saturated water [5]. (Digital denotation as on Fig. 1.)

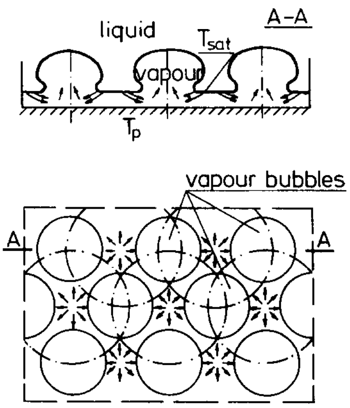

FIG. 5. The simplified model of film boiling on a plane, horizontal heating surface. In the region marked with the dotted line the axisymmetrical stagnation flow of vapour occurs, as under the droplet (Fig. 3(a)).

hypothesis of diffusive vapour microlayer in transition boiling, as on Fig. 2.

The direct comparison of the calculated values of $T_{p,min}$ from the dissipative model for $p \leqslant 15 \times 10^5$ Pa with experimental results of Yao and Henry [5], Fig. 4, allows one to state that for this model the best agreement is achieved in the whole examined range of pressure. It should be stressed that only one experimental constant, i.e. the exponent x (21), was used for determining $T_{p,min}$ in this model. Due to the observed similarity between the flow in the vapour film under a droplet and the flow in the film among neighbouring bubbles in a large pool, Figs. 3 and 5, the obtained results, Figs. 1 and 4, should be regarded as equally appropriate for both of these cases.

9. CONCLUSIONS

The method of description of the film boiling crisis by means of the variational hypothesis of non-equilibrium phase change is based on the assumption, that evolution of thermodynamic systems proceeds into the direction of stationary states and can be described by a local potential. This statement is correct for the systems not deviating much from the stationary states. For determining the limiting boundary conditions, for which non-equilibrium phase change takes place it is necessary to know the local EQ transfer in two competitive systems. In the considered example of the film boiling crisis it was assumed that convection either in the vapour film or in the liquid boundary layer is described by the combination of stagnation and creeping flows. It was also assumed that for the isothermal heating surface the ratio of heat fluxes, received from this surface by liquid and vapour is determined by the relation $[h_{lv}c_{p,v}^{-1}(T_p - T_{sat})^{-1}]^x$ with an experimentally correlated value of the exponent x [1, 2, 5, 26]. Local potentials for the vapour and liquid phase were found by assuming: constant pressures at the limits of the considered control volume, constant temperature of the heating surface and the saturation temperature at the limit of a control volume for the vapour film, and the temperature calculated from the ratio of heat fluxes for the liquid phase.

According to the variational hypothesis, the heating surface temperature for which dissipation of energy measured by the value of the local potential will be identical in both phases is the temperature of film boiling crisis.

The model presented for the film boiling crisis concerns the isothermal heating surface and saturated liquid. It is the consecutive attempt of employing the variational hypothesis of phase change [15] previously used for analysing the nucleate boiling crisis [20, 21].

Generally, the dissipative models of film and nucleate boiling crisis are the attempts to introduce the apparatus of non-equilibrium thermodynamics to the theoretical analysis of boiling processes.

Acknowledgements—I would like to thank Professor B. Staniszewski for numerous remarks and valuable discussions concerning the subject of the paper. This study was accomplished as part No. 2.06 within the scheme of Research Problem MR I-10 entitled "Optimization of Thermodynamic and Flow Problems" financed by the Polish Ministry of Science and Higher Education and coordinated by the Institute of Heat Engineering and Combustion Engines of Poznań Technical University.

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UN MODELE A DISSIPATION DE LA CRISE D'EBULLITION EN FILM

Résumé—On a presenté un modèle à dissipation de la crise d'ébullition en film, fondé sur l'hypothese variationelle d'une transition de phase non-équilibre. On a construit les systèmes de transport, caracteristiques pour d'ébullition en film et de transition pour la goutte du liquide sur la surface chauffante horizontale et plate. La valeur de la température minimale d'ébullition en film—$T_{p,min}$—calculé à l'aide du critere d'équivalence des potentiels locaux. On a calculé les courbes $p = p(T_{p,min})$ pour l'eau en modèles hydrodynamiques et thermodynamiques et comparé avec les résultats pour le modele a dissipation.

DISSIPATIONSMODELL DER FILMSIEDEKRISE

Zusammenfassung—Ein Dissipationsmodell der Krise vom Filmsieden wurde, das an wariable Hypothese von ungleichgewichten Phasenübergängen angelehnt wurde, dargestellt. Ubergangssysteme wurden konstruiert, die für Filmsieden und Ubergangssieden des Flüssigkeitstropfens auf flache waaggerechte und isotermische Heizoberfläche charakteristisch sind. Der Mindestwert des Filmsiedepunktes $T_{p,min}$ wurde mit der Hilfe des Kriteriums lokaler Gleichheiten von Potenzen für zwei mit sich in der Konkurenz stehenden Ubergangssysteme berechnet. Es wurden Kurven $p = p(T_{p,min})$ für Wasser für hydrodynamische und thermodynamische Modelle bezeichnet und sie wurden mit den, für das Dissipationsmodell erzielten Ergebnissen verglichen.

ДИССИПАТИВНАЯ МОДЕЛЬ КРИЗИСА ПЛЕНОЧНОГО КИПЕНИЯ

Аннотация—На основе вариационной гипотезы неравновесных фазовых превращений создана диссипативная модель кризиса пленочного кипения. Построена характеристика для систем переноса при пленочном и переходном кипении жидкой капли на плоской горизонтальной и изотермической поверхностях нагрева. Используя равенства локальных потенциалов двух сравниваемых систем переноса, рассчитана минимальная температура пленочного кипения $T_{\mathrm{p,min}}$. Построены кривые p–$p(T_{\mathrm{p,min}})$ для гидро-и термодинамических моделей кризиса пленочного кипения воды и приведено их сравнение с результатами, полученными для диссипативной модели.