Multifactoring Concept – a Key to Investigation of Forced-Boiling in Microsystems

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Abstract. In the present paper forced-boiling in microsystems is considered in the light of fundamentals of boiling heat transfer such as local temperature pulsations of heating surface (Moore and Mesler, 1961), pumping effect of growing bubble (PEGB) (Shekriladze, 1966), a model of "the theatre of director" (MTD) (Shekriladze and Ratiani, 1966) and multifactoring concept (MFC) (Shekriladze, 2006). An attempt is made to resolve a contradiction between accordance of heat transfer process to developed boiling heat transfer law in the major part of experiments and qualitatively differing trends in the other part of processes. The problem of interpretation of generation of strong reverse vapor flows, related cyclical oscillations and flow instabilities also is touched. According to presented analysis leading role in specific thermo-hydrodynamic characteristics of boiling microsystems is played by so-called duration-dependent multifactoring which, by its part, is linked to transition to prolonged action of microlayer evaporation (MLE) and PEGB. As a result drastically increases a number of influencing heat transfer factors extremely complicating description of the process. At the same time prolongation of intensive stage of acting of MLE and PEGB creates prerequisites for specific thermo-hydrodynamic appearances.

Keywords: heat transfer, forced-boiling, microsystems, multifactoring, thermo-hydrodynamic effects.

1. Introduction

During last decades, among various applications of boiling processes, boiling in microsystems has gained high priority in terms of development of microelectronics. Importance and complexity of the problem adequately is reflected by unrelenting intensity of experimental and theoretical studies although this research is affected by essential lag in development of general boiling heat transfer theory.

Beginning from Jakob (1949), Kruzhilin (1948) and Rohsenow (1952) development of boiling heat transfer theory was based at approaches connecting HTC to intensity of certain cooling mechanism (an actor) (a model of "the theatre of actor" (MTA)).

MTA presents efficient universally adopted way of analysis in convection heat transfer theory. However, developed boiling heat transfer manifests exceptionally specific sequence of causes and effects excluding adaptability of MTA.

Among basic steps qualitatively deepening understanding of boiling phenomenon firstly should be mentioned discovery of local temperature pulsations of heating surface synchronous with a bubble formation and departure cycle (Moore and Mesler, 1961).

Another qualitative step was made through prediction of existence of so-called pumping effect of growing bubble (PEGB) leading to strong microcirculation of liquid in the zone of nucleation site (Shekriladze, 1966).

Further, based at these features, alternative to MTA model of "the theatre of director" (MTD) has been offered by Shekriladze and Ratiani (1966) revealing crucial role of so-called effective radii of nucleation sites. As a result, universal MTD-based correlation was developed describing experimental data on HTC during developed boiling of all classes of liquids including liquid metals and cryogens. Afterward MTD has been amplified by so-called multifactoring concept (MFC) (Shekriladze, 2006) topical just in the context of boiling in microsystems.

Alongside with this, unfortunately, since 1960s, aforementioned fundamentals were not efficiently used through development of boiling heat transfer theory.

Longstanding disregard of MTD has led to essential incompleteness of experimental studies performed, as a rule, without investigation of nucleation sites. Numerous unsuccessful attempts were made by the goal to develop improved MTA-based correlations (including unworkable attempts to substitute standard roughness parameters for the effective radii of nucleation sites). MTA-based approaches turned out to be incapable to interpret strong conservatism of developed boiling heat transfer law irrespective of drastic changes of internal structure of two-phase system taking place with variation of mass acceleration or subcooling of bulk liquid.

As regards to boiling in microsystems, even qualitative interpretation of revealed in these systems specific features has met principal difficulties.

These and other principal problems affecting development of boiling heat transfer theory have become a subject of discussion summarized in (Shekriladze, 2008).

It is shown that MTD in combination with MFC represents unified framework for investigation of diversity of boiling heat transfer curves. In particular, multifactoring phenomenon may serve as a basis for qualitative and quantitative interpretation of specific thermo-hydrodynamic features characteristic for boiling in microsystems.

2. MTD and MTD-Based Correlation

By common agreement developed boiling is linked to decisive contribution of cooling mechanisms unique to boiling itself. Developed boiling is observed in rather wide range of heat fluxes between the zones with tangible effect of natural or forced convection and boiling crisis. This is why this mode may cover different ranges of heat fluxes at constant pressure depending on geometry of boiling surface, intensity of gravity field, subcooling or liquid flow.

However, developed boiling heat transfer law remains uniform in such differing conditions (Shekriladze, 1981; 2007; 2008).

MTD proceeds from the peculiarities of local temperature pulsation of boiling surface. Basic importance is attached to coincidence of the burst of cooling effect with onset of a bubble growth and short-run character of cooling effect (duration of intensive cooling is far less than duration of the bubble growth and departure cycle).

MTD considers observed strong cooling effect as a result of launching of specific mechanisms of liquid phase convection and immediate evaporation by the onset of a bubble growth. Besides, primary role is attached to liquid phase convection.

MTD links the burst of liquid phase convection to PEGB. The burst of immediate evaporation is linked to MLE. Onset of a bubble growth takes place at the instant the average temperature of the meniscus of critical size overcomes the temperature of thermodynamic equilibrium in the system nucleus-liquid-site. Finally, MTD assumes regulation of boiling HTC by nucleation through multiple triggering of short-run actions of PEGB and MLE together with fitting of the number of operating sites to required superheat, irrespective changes in intensities of separate cooling mechanisms.

MTD-based correlation of developed boiling heat transfer incorporates so-called one-parameter model of boiling surface consisting unlimited number of identical conical recesses satisfying the following condition:

$$\frac{1}{2}\beta < \theta < 90^0 \qquad (1)$$

In Eq. 1 β is cone angle of the recess serving as a nucleation site; θ is wetting angle. In the similar site minimum curvature radius of the nucleus (effective radius of nucleation site ρ_0) is equal to the radius of the mouth of the recess (Griffith and Wallis, 1960).

Finally MTD leads to the following correlation for developed boiling HTC (Shekriladze and Ratiani, 1966) (left out details are reflected in (Shekriladze, 1981; 2008):

$$Nu = 0.88 \cdot 10^{-2} K^{0.7} \operatorname{Re}_*^{0.25}, \qquad (2)$$

where: $Nu = \dfrac{h\rho_0}{k}$; $\quad K = \dfrac{q\rho_0^2 r \rho_g}{\sigma k T_s}$

$$\operatorname{Re}_{*,s} = \frac{C_p \sigma \rho T_s}{r^{3/2} \rho_g^2 \nu}$$

Here h is heat transfer coefficient (HTC); q is heat flux; r is heat of evaporation; σ is surface tension; T_s is temperature of saturation; ρ_g is density of vapor phase, k, C_p, ρ and ν are thermal conductivity, heat capacity, density and cinematic viscosity of liquid phase, respectively.

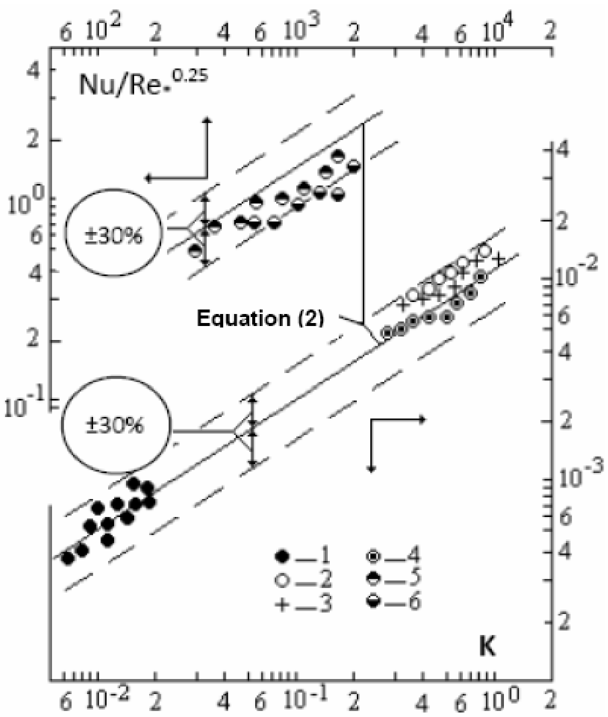

Fig. 1. Correlation of experimental data on developed boiling on the surfaces with the known values of ρ_0: 1 – sodium (Marto and Rosenow, 1966), ρ_0 = 50 μm; 2-4 – water (Shoukri and Judd, 1975), ρ_0 = 5 μm; 5 – R 12 (Chumak et al, 1979), ρ_0 = 86 μm; 6 - R 22 (Chumak et al., 1979), ρ_0 = 86 μm.

Fortunately, a small number of experiments including the values of effective radii cover greatly differing boiling areas and materials of heating surfaces (Marto and Rosenow, 1966; Shoukri and Judd, 1975; Chumak et al., 1979). In this context a correlation presented in Fig. 1 reflects universal character of Eq. 2.

Absence of data on ρ_0 in a majority of experimental studies is mitigated by wide use of commercial heating surfaces (mainly rolled tubes) roughly corresponding to one-parameter boiling surface with the average effective radius equal to 5 μm.

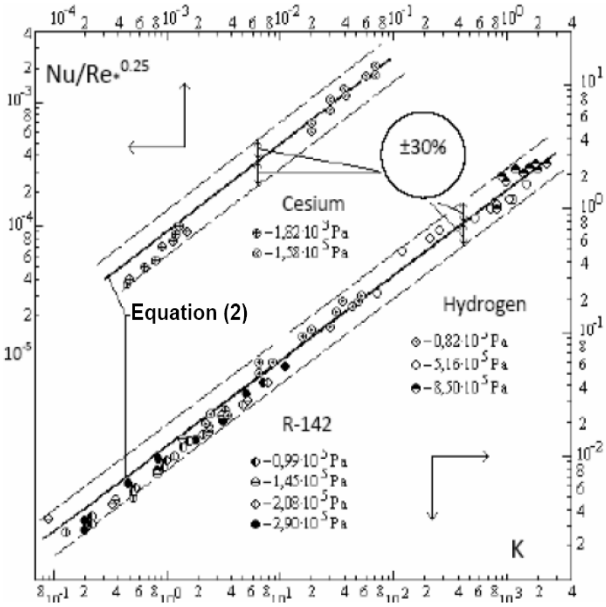

Fig. 2. Correlation of experimental data on developed boiling of cesium (Subbotin et al., 1976), R 142 (Danilova, 1976) and hydrogen (Grigoriev et al.. 1975) on commercial surfaces (ρ_0= 5 μm).

In Fig. 2, as an example, correlation of experimental data on boiling on commercial surfaces of the most "inconvenient" liquids (liquid metal, refrigerant and cryogen) is presented. Eq. (2) describes wide experimental data on developed boiling heat transfer of all groups of liquids without matching different constants and powers to different surface-liquid combinations(Shekriladze, 2007).

3. Multifactoring phenomenon

According to equation (2) HTC depends only on two "external" factors - heat flux and effective radius. Such a conservatism of developed boiling heat transfer can be linked to following three basic conditions:

- Triggering of short-run actions of cooling mechanisms by bubble growth onset;
- Existence of great (practically unlimited) number of stable nucleation sites with

roughly uniform effective radii irrespective are they operating or potential;

- Prevailing contribution of heat removal by liquid phase convection.

According to multifactoring concept (MFC) (Shekriladze, 2006) a failure to meet any these conditions results essential transformation of heat transfer regularities. At that the circle of influencing HTC factors may be widened by parameters of inter-phase hydrodynamics, body force, contact angle, subcooling, sizes, form, orientation and thermal characteristics of heating surface, distribution of nucleation sites, and prehistory of the process.
As it follows from qualitative consideration, there can be distinguished two main types of multifactoring:

- The first – connected with onset of dependence of effective radius on a degree of penetration of liquid into nucleation site (wetting-dependent multifactoring),
- The second – connected with transition to prolonged duration or uninterrupted regime of action of any intensive cooling mechanism (duration-dependent multifactoring).

3.1 Wetting-dependent multifactoring

Wetting-dependent multifactoring occurs at the condition $\beta/2 > \theta$ when effective radius of nucleation site stops to be a constant equal to the radius of the mouth of the recess (Fig.3). As it can be shown through simple analysis, in this case effective radius of the site may be determined by following relationship:

$$\rho_0 = \frac{R}{\cos(\beta/2 - \theta)}(1 - l/L) \qquad (3)$$

As it follows from equation (3), effective radius undergoes wide-ranging variation with penetration of liquid into site. Besides, ρ_0 may be not only much less of R but even greater than R (in the case $l << L$).
Conditions of bubble growth onset in operating sites qualitatively differ from potential sites. As transverse size is much smaller far down from the mouth, the first onset of bubble growth in a potential site requires much higher superheat than onset of any subsequent bubble growth. In such a situation the transition of potential site to active condition and vice versa can occur only at markedly different superheats which in fact is the basis of the hysteresis phenomenon.

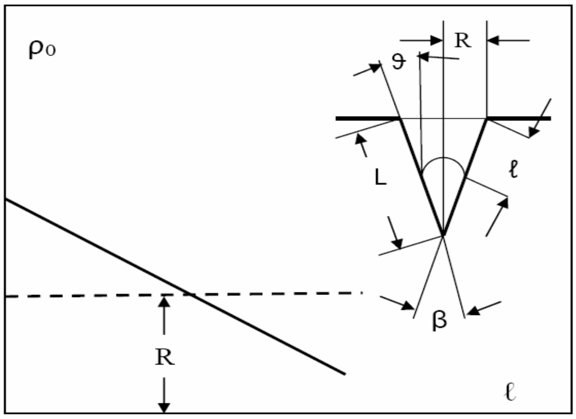

Fig. 3. Dependence of effective radius on a degree of wetting of nucleation site by liquid phase in the case $\beta/2 > \theta$.

Wetting of the site, in general, represents dynamical process depending on velocity and duration of wetting. These parameters, for its part, may be influenced by contact angle, heat flux, prehistory of the process, capability of heating surface to concentrate heat in the zone of wetting meniscus. If wetting length l is small, two highly differing levels of the parameter ρ_0 take place, the one of order of the radius of the mouth in operating sites and the other, very low one, in potential sites.
Idealized two-parameter model of such a boiling surface (Shekriladze, 1981) allows to interpreting specific families of heat transfer hysteresis curves obtained in experiments on boiling of helium (Andreyev et al., 1978).
Differing situation is to be observed on the heating surface providing stable and uniform effective radii of operating and potential sites even in the case $\theta = 0$. According MTD-MFC such a heating surface should not exhibit boiling heat transfer hysteresis.
This conclusion can be illustrated by experimental data (Grigoriev et al., 1973) on boiling heat transfer hysteresis during boiling of cryogens manifesting itself vastly on rough surfaces and virtually absent on polished ones.

In the framework of MTD-MFC it also presents significant interest analysis of contradictory experimental data on influence of thermal parameters of heating surface on HTC presented in (Shekriladze, 2008).

Despite significant increase of the number of influencing factors, bubble growth onset preserves the role of regulator of average HTC during wetting-dependent multifactoring.

At the same time, in contrast to developed boiling, heat transfer gains significant new peculiarities quantitative description of which requires modification of MTD taking in account dependence of effective radius on several influencing factors.

3.2 Duration-dependent multifactoring

Duration-dependent multifactoring quite often may occur consequent to developed boiling, for instance, through transition to prolonged or even uninterrupted action of PEGB or MLE with structural transformation of two-phase flow. Similar transition also may take place with change of intensity of body force or with variation of inclination angle of heating surface in the gravity field.

Establishment of conditions of transition to duration-dependent multifactoring is much more complex problem. Clarification of regularities of such a transition requires consideration of structural development of corresponding two-phase flow that represents independent multifaceted problem.

At the same time, duration-dependent multifactoring results transition to heat transfer process corresponding to MTA. Thereby, in connection with diversity of cooling mechanisms, the problem of theoretical assessment of HTC becomes extremely complex. It requires comprehensive multifactorous numerical modeling of all details and stages of operation of different cooling mechanisms (similar to an attempt made in (Basu et al, 2005) for the case of subcooled flow boiling).

4. Forced-Boiling in microsystems

Available experimental data on forced-boiling in mini-and-microchannels reveal wide diversity of two-phase structures, specific thermo-hydrodynamic effects and heat transfer curves. According detailed experiments on forced boiling of Fluorinert FC-77 in microchannels of rectangular section (Harirchian and Garimella, 2009) flow patterns identified through high-speed visualizations can be categorized into six major flow regimes – bubbly, slug, churn, wispy-annular, annular, and inverted-annular flows (the latter in a post-dryout regime).

At the same time tangible part of a channel may be covered by intermittent regimes (e.g., intermittent churn-annular flow).

It also is concluded that flow regime maps developed for large channels or for adiabatic two-phase flow are not appropriate for predicting boiling regimes in microchannels. Thereby unambiguously is demonstrated existence of strong feedback effects between hydrodynamics and heat transfer.

4.1 Thermo-hydrodynamic peculiarities

Thermo-hydrodynamic feedback effects especially manifest itself through generation of strong reverse vapor follows, related cyclical oscillations and flow instabilities observed in minichannels and microchannels (Qu and Mudawar, 2004; Kandklar, 2004; Cheng et al. 2006; Kuo and Peles, 2008). Besides, the nature of observed thermo-hydrodynamic feedback effects still remains to be identified.

Similar to aforementioned problems in pool boiling heat transfer research, there it also exist contradictory experimental data on boiling in the microsystems. A part of the data shows accordance of heat transfer process to developed boiling law and another part demonstrates qualitatively differing trends.

For instance, according to aforementioned detailed study (Harirchian and Garimella, 2009) in microchannels of width 400 μm and larger, in full accordance with MTD and MTD-based correlation, HTC remains independent of mass flux regardless of the channel size and the flow pattern in wide range of heat flux. In the microchannels of width 100 and 250 μm the same accordance is suppressed at relatively low heat fluxes.

Correspondence of experimental boiling heat transfer curves to developed boiling heat transfer law is observed in majority of experiments (Bao et al., 2000; Thome, 2006; Liu and Garimella, 2007). At the same time another part of the same and other experiments demonstrates qualitatively differing trends.

Unfortunately, research of diverse thermo-hydrodynamic effects is affected by delay with development of adequate physical models. Suggested correlations of existing data on HTC and CHF have restricted application. There also are problems with correct choice of strategies of experimental research. For instance, it still is disregarded crucial role of effective radii of nucleation sites.

During experimental investigations of flow regimes with prevailing role of MLE insufficiently is taken in account the role of thermal parameters of heating surface although significance of such an influence is demonstrated by theoretical and experimental studies (Ratiani et al., 1969; Shekriladze and Rusishvili, 1987; Hetsroni et al., 2005).

As it follows from qualitative analysis (Shekriladze, 2006; 2008), seeming chaos in the experimental data, similar to cases considered above, can be resolved in the framework of MTD-MFC.

4.2 Potential role of PEGB and MLE

In general, geometry and transverse sizes of microchannels support formation and longstanding preservation of vapor plugs shifting through a channel. For instance, according (Harirchian and Garimella, 2009), if bubbly and intermittent churn-wispy-annular flows prevail at comparatively large widths of the miicrochannel (up to 5850 μm), a slug and intermittent churn-annular flows become dominant with reduction of the width to 250-100 μm at uniform for all experimental channels depth 400 μm. (Fig.4).

According to (Shekriladze, 1966) PEGB is driven by sharp variability of intensity of evaporation on a bubble interface in the liquid boundary layer with initial high gradient of temperature (to be more exact, by corresponding more sharp variability of reactive force applied to the same interface).

At the same time an attempt is made to link speed-up of liquid flow to tangential forces occurred on the bubble surface caused by the same variability of reactive force (a version of "tangential driving").

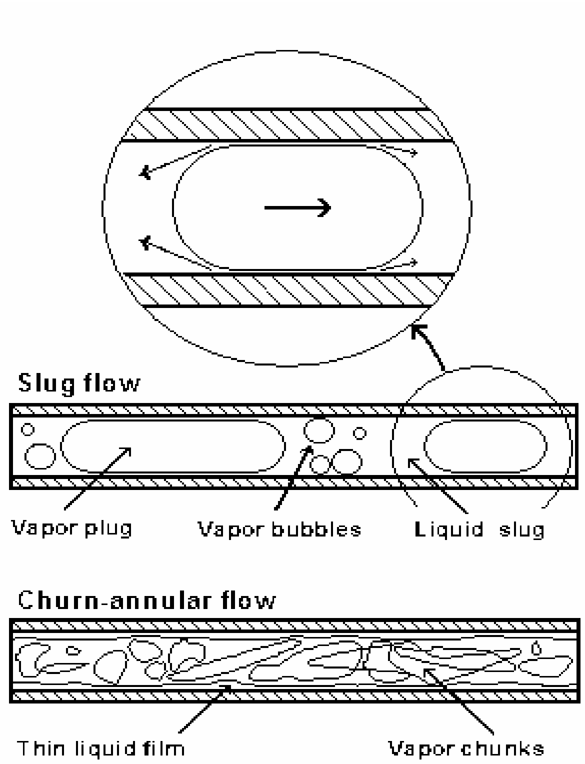

Fig. 4. Dominant flow regimes during boiling of Fluorinert FC-77 in microchannel with the width 100 μm (Harirchian and Garimella, 2009).

However, through further analysis (Shekriladze et al., 1980; Shekriladze, 1982), priority is given to the version of the speed-up under influence of volume force occurring in adjacent to the bubble liquid layer under influence of the same variability of reactive force (to say, the same pressure gradient on the bubble interface).

The matter is that interpretation of fixed in experiments intensities of PEGB (e.g. speed-up of liquid jet up to 2 ms^{-1} during around 2 ms) through "tangential driving" requires unrealistically high velocities on the bubble interface. At the same time the same pressure gradient applied to interface and acting as volume force within liquid boundary layer (Schlichting, 1979) generates mass acceleration of order 10^3 ms^{-2} and more.

It turns out that all types of "tangential driving", including Marangoni effect, may contribute only in quite weak near-bubble convection. Even comparatively weak, near to steady-state butterfly-like double-jet flow (Wang, 2005) turns out to be driven by volume force (Shekriladze, 2008).

Introduction of aforementioned postulate of the theory of boundary layer involves necessity of determining of geometry of liquid boundary layer that in general presents not so easy problem. Regarding to vapor plug shifting in microchannel (Fig. 4), wedge-shaped gap between the plug and the channel naturally shapes the area where PEGB is launched.

In a channel of very small diameter a vapor plug shifts in near to steady-state regime. Variability of evaporation on the plug interface in the zone of the gap apex is much less sharp than in the case of initial boiling that causes weakness of PEGB. It should be noted also that in the similar gap PEGB gains the form of three-dimensional multi-jet flow (with alternation of the zones of liquid suction and rejection) (Shekriladze, 2008).

Despite of comparative weakness, however, the effect may contribute in specific features of boiling Microsystems.

In particular, shifting of vapor plug leads to different conditions of evaporation at its different sides (Fig. 4). Liquid layer between the plug and heating surface naturally becomes thinner to the back side of the plug causing more intensive manifestation of PEGB there. As a result multi-jet flow is weaker at leading side of the plug.

Corresponding dynamical imbalance of shifting plug is considered in (Shekriladze, 2008) as possible basis of such a specific operation features of pulsating closed loop heat pipe as self-start-up and periodical reverse of circulation of heat carrier (Qu and Ma, 2007; Yang et al., 2008).

Much more intensive manifestation of PEGB can take place at leading vapor plug in near to critical (pre-crisis) regime of microchannel flow.

As it follows from Fig.5, at certain stage of pre-crisis regime, leading vapor plug may reduce to spherical meniscus with frontal triple contact line at back boundary of dried and superheated part of boiling surface. Besides, excess heat of dried zone just is focused to triple contact line. As a result preconditions are created for strong manifestation of PEGB.

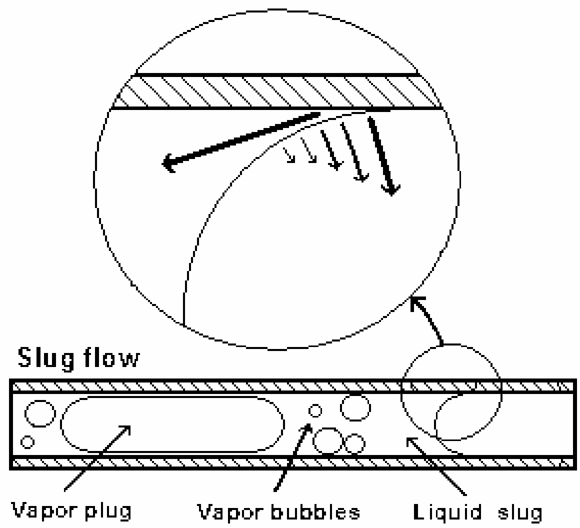

Fig. 4. Leading vapor plug in near to critical (pre-crisis) regime.

In such a manner, during pre-crisis regime, PEGB may achieve quite high intensity contributing in generation of strong reverse vapor flows, related cyclical oscillations and flow instabilities observed in microsysems. At that it also should be taken in account potential significant role of capability of heating surface to redistribute excess heat.

Conclusions

Unified framework MTD-MFC and, in particular, the concept of duration-dependent multifactoring open the way to comprehensive research of important problem of boiling in the microsystems. It is necessary to upgrade existing physical models taking in account thermo-hydrodynamic consequences of prolongation of intensive action of PEGB and MLE. It also should be properly taken in account essential role of capability of heating surface to redistribute heat flow. It deserves close attention potential role of PEGB in generation of strong reverse vapor flows, related cyclical oscillations and flow instabilities observed in minichannels and microchannels.

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