ABSTRACT

A major detriment of two-phase microscale flow systems is a relatively high pressure drop, as well as the potential for flow instabilities. A possible mechanism to overcome these disadvantages is vapor extraction through a hydrophobic porous wall in the channel to reduce vapor content and suppress vapor expansion. The vapor extraction may occur either as evaporation, bubble extraction or a mix of both. For the design of vapor extraction systems, it is important to accurately predict extraction regimes, extraction rates and the effect of extraction on the heat transfer and flow conditions. This study focuses on two parts: the development of physic-based models for the transition criteria among (i) the extraction mechanism regimes, and (ii) the extraction flow regimes for microscale flow boiling. The identification and conditions for the various extraction regimes are discussed and criteria for transition are developed based on physical concepts. Six potential extraction mechanism regimes are identified: (a) no extraction, (b) pure evaporation, (c) pure bubble extraction, (d) bubble extraction with partial liquid blockage, (e) bubble extraction with evaporation, and (f) liquid breakthrough. Based on the criteria for the extraction mechanism regimes, the rate of vapor extraction is modeled and used to analyze the effects of vapor extraction on the dynamics of two-phase flow boiling. The results show six extraction flow regimes for two-phase flow boiling: (i) single-phase evaporation, (ii) two-phase evaporation – bubble collapse, (iii) full extraction - stable, (iv) full extraction - unstable, (v) partial extraction – stable and (vi) partial extraction – unstable.

INTRODUCTION

Due to the wide development of performance and miniaturization of electronic devices in the last few decades, the large increase in heat dissipation per unit volume of the devices has become a major concern as most applications are required to operate at a relatively uniform and stable temperature. A two-phase microscale heat sink has been proposed because of its high surface to volume ratio and large heat transfer coefficient. Especially for two-phase flow boiling, the additional advantage is the relatively small streamwise temperature variation compared to single-phase applications as the saturation temperature of the fluid only varies with pressure. However, the major undesired issues of flow boiling in microchannels are a large pressure drop and flow instabilities [1-2]. A large pressure drop can lead to large temperature variation along the flow in the two-phase regime. Also, the large pressure drop and thermal oscillations due to flow instability may lead to severe mechanical vibration and dry-out [1].

Since flow instability is a severe issue associated with flow boiling in microchannels, numerous investigators [2-10] have proposed channel modifications as a means to suppress it. These stabilizing methods may be categorized into three main groups: (i) using an inlet restrictor, (ii) application of engineering nucleation sites, and (iii) using an expanding or diverging channel. The first group [2-4] stabilizes flow boiling by placing a flow restrictor at the inlet to decrease reverse flow of vapor. However, the drawback of this method is a large increase in the pressure drop of the system [5]. The second group [5-7] fabricates artificial nucleation sites on the channel walls. This reduces the required superheat surface temperatures and thereby reduces the rapid expansion of bubbles. The third group [5, 8-10] evaluates flow boiling inside channels with increasing cross-sectional area along the flow direction. As the cross-sectional area increases, bubbles tend to expand downstream rather than upstream, leading to less reverse flow of vapor.

In addition to the channel modification methods mentioned above, Salakij et al. [11] proposed that in-situ vapor extraction might be used as an alternative method to stabilize flow boiling. The main concept of in-situ vapor extraction is to locally
extract the generated vapor out of the channel through a hydrophobic porous wall as a means to reduce or control the vapor fraction inside the channel. Schematic representation of an in-situ vapor extraction in two-phase heat sink is shown in Figure 1. Salakij et al. [12-13] developed a one dimensional predictive model for flow boiling in microscale diverging channels coupling with in-situ vapor extraction. The results show significant improvement to the allowable stable heat flux when compared to flow boiling in a straight channel without in-situ vapor extraction.

Apart from the ability to stabilize the flow, several studies [14-19] suggest that in-situ vapor extraction also has the potential to reduce the system pressure drop while maintaining the benefit of enhanced heat transfer. Apreoitesi et al. [14-15] investigated diabatic boiling water flowing through a fractal-like branching microchannel network with in-situ vapor extraction. The experimental results show a decrease in the system pressure drop with increasing extraction pressure differential across the porous wall. A later work by Salakij et al. [19], which developed a one dimensional predictive model and validated it by using the experimental results obtain in [14-15], shows up to a 70% decrease in the overall pressure drop. Moreover, the bulk fluid temperature within the channel decreases which shows the potential of in-situ vapor extraction to decrease overall operating temperature of the device. David et al. [17] investigated two-phase flow in parallel microchannels coupled with venting, where the flow and vent channels are separated by hydrophobic porous membrane, and shows a significant decrease in pressure drop. The computational model of the vapor-venting process studied by Fang et al. [18] also confirmed this result showing that vapor-venting helps suppress local dry-out in microchannels.

In order to fully utilize the potential of in-situ vapor extraction for two-phase flow, it is necessary to understand the effects of vapor extraction on heat transfer and flow conditions. Basically, effects of vapor extraction are directly related to the vapor extraction mass flow rate. Many studies [12-20] have predicted the vapor/gas transport across the membrane rate based on Darcy's law as:

\[ V_{\text{extr}} = \frac{K}{\mu_v} \nabla P_{\text{extr}} \]  

where \( K \) is the specific membrane permeability, \( \mu_v \) is the vapor dynamic viscosity, and \( \nabla P_{\text{extr}} \) is the pressure gradient across the membrane. The model may indeed require added complexities to be accurate for this application. For example, Salakij et al. [12, 19] related vacuum membrane distillation to vapor extraction and included evaporation effects on the vapor extraction where the evaporation rate is based on the local vapor pressure gradient across the membrane. Cappello et al. [21] used the dusty gas model, which is a general form of Darcy's law, with the added effect of membrane compaction to successfully predict gas and superheated vapor transport through the membrane.

Several studies suggested that two-phase hydrodynamics and other conditions also affect the vapor extraction. Alexander and Wang [22] studied vapor separating from a two-phase microscale flow through a hydrophobic porous plate, called a breather. The correlation was developed based on the assumption that the extraction rate is also related to flow velocity as a function of the ratio of the pressure differential across the porous plate to the pressure drop associated with drag on the bubble. Xu et al. [20] studied gas bubble removal in a microscale channel and proposed criteria for completely removal of a gas bubble by considering film formation, bubble size, and liquid breakthrough conditions. Cappello et al. [21] studied gas and vapor transport through a porous membrane and showed the deviation of extracted mass flow rate from single-phase transport studies, when saturated vapor is extracted from a saturated liquid-vapor mixture. They proposed that these results may be caused by effects of two-phase hydrodynamics at the membrane surface and condensation within the membrane. Based on these observations, it is important to identify the extraction mechanism regime in predicting mass extraction rates. As an analogy to two-phase flow regimes, the extraction mechanism regimes should represent the variation in the physical conditions of the extraction process.

An ability to predict two-phase flow regimes is important to the development of flow regime-based pressure drop and heat transfer models [23]. Two-phase flow regime maps are used as a tool to identify the transition of flow patterns based on different operating conditions. The methods to develop a two-phase flow regime map may be either empirical or physics-based. There are several studies that generate regime maps for microchannel flow using empirical methods, (e.g. [23-24]). For flow boiling with vapor extraction, David et al. [25] observed two-phase flow regimes in a vapor-venting microchannel. Based on their flow visualization, stratified flow, which is rarely observed in other microscale geometries, was found for low liquid velocities. However, at higher liquid velocities annular flow is dominated. In contrast to empirical methods, there are only a few studies that have developed regime maps using physics-based relationships, such as the pioneering work by Taitel and Dukler [26], and the later work by Barnea et al. [27]. This approach generally uses a dimensionless form of basic relationships to predict the conditions for flow regime transition. Each regime transition criterion is normally developed individually resulting in a relation of different dimensionless parameters.

Similar to the identification of two-phase flow regimes, extraction is expected to also have characteristics which can be
classified into different extraction regimes. The goal of this study is to develop physic-based models for the transition criteria among specific identified regimes for vapor extraction. The extraction models are expected to help the development of regime-based extraction mass flow rate predictions in two-phase flow, as well as being a useful design tools for enhanced performance of liquid-vapor systems.

PHYSICS-BASED REGIME MAP

The methodology used to develop a physics-based regime map can be divided into four main steps: (i) identify possible regimes and physical conditions for each regime, (ii) develop theoretical models for transition between physical conditions, (iii) nondimensionalize the transition criteria, and (iv) plot transition criteria on an appropriate map that represents transition conditions. The additional step to make a regime map more practical for a specific application is converting the nondimensional map into a dimensional map for a specific set of conditions, such as a working fluid and flow geometry. This step is usually necessary because the nondimensional map that identifies all considered regimes and parameters may be excessively complicated and multidimensional to be used as a design tool. For example, Taitel and Dukler [26] developed four transition criteria to separate five flow regimes resulting in the two-phase flow regime map based on four different dimensionless parameters. This nondimensional map is then converted to the commonly known dimensional flow regime map based on liquid and vapor superficial velocity coordinates for specific geometries and working fluids.

The extraction map is to be developed to identify different physical conditions related to vapor extraction, help understand the potential of vapor extraction and ultimately to be used as a design tool. In this study, two main types of extraction maps are proposed: (i) extraction mechanism map, which characterizes how vapor is being extracted, and (ii) extraction flow map, which characterizes the results of flow boiling on vapor extraction. Instead of developing a single extraction regime map that includes all considered extraction regimes, this study will focus on the development of each individual regime transition and the corresponding individual map for each specific regime transition which ultimately could be further combined to an extraction regime map.

EXTRACTION MECHANISM REGIMES

To develop the extraction mechanism map, the first step is to identify the extraction mechanism regimes. It is important to understand the membrane transport mechanism such that the developed extraction mechanism regimes capture all of possible different behaviors of extraction. Membrane transport is usually initiated by applying a pressure differential across a porous membrane. For hydrophobic porous membrane, the liquid phase is suppressed from leaking into the membrane pores by surface tension forces. If the pressure difference across the membrane is sufficient to overcome the surface tension forces, there will be a liquid breakthrough which is normally an undesirable situation. This upper limit on the pressure differential across the membrane is defined as the breakthrough pressure. By applying Young-Laplace equation for a straight capillary pore, the breakthrough pressure is estimated as:

$$\Delta P_{\text{break}} = \frac{4\sigma_{lv} \cos \theta_{c,\text{mem}}}{d_p}$$

where $\sigma_{lv}$ is the liquid-vapor surface tension, $\theta_{c,\text{mem}}$ is the liquid phase contact angle on the membrane, and $d_p$ is equivalent pore size of the membrane. It should be noted that although this breakthrough pressure can be theoretically estimated using the above relationship, many studies experience breakthrough at much lower pressure differential [17, 20, 22, 25]. This may be because of inconsistencies of membrane pore manufacture and also the more complex nature of porous membranes having a range of pore sizes and shapes.

Vapor extraction can occur in two modes: bubble extraction and evaporation. Bubble extraction is a result of hydrodynamic transport, i.e. the vapor phase is extracted through a membrane directly by the pressure differential across the membrane. The evaporation is a result of thermodynamic transport where the liquid phase at the membrane evaporates and transports across the membrane via thermal and pressure forces. The evaporation occurs when the vapor pressure of the liquid in contact with membrane is greater than the extraction pressure on the opposite side of the membrane. More detail explanation of the evaporative transport mechanism can generally be found in discussions of vacuum membrane distillation application, e.g. [28-31]. It should be noted that both modes of vapor evaporation can coexist depending on extraction condition and whether liquid, vapor or both phases are in contact with membrane. The physical conditions of vapor extraction and breakthrough are summarized in Table 1.

Table 1. Mechanism and conditions of membrane transport.

<table>
<thead>
<tr>
<th>Transport mode</th>
<th>Mechanism</th>
<th>Phase transport</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evaporation</td>
<td>Thermodynamic transport</td>
<td>Vapor</td>
<td>Liquid in contact with hydrophobic membrane</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Saturation pressure of liquid at membrane interface is higher than extraction pressure</td>
</tr>
<tr>
<td>Bubble extraction</td>
<td>Hydrodynamic transport</td>
<td>Vapor</td>
<td>Bubble in contact with hydrophobic membrane</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bubble pressure is higher than extraction pressure</td>
</tr>
<tr>
<td>Breakthrough</td>
<td>Hydrodynamic transport</td>
<td>Liquid</td>
<td>Pressure differential across the membrane is greater than breakthrough pressure</td>
</tr>
</tbody>
</table>

Copyright © 2013 by ASME
Extraction mechanism regimes are classified by using membrane transport mechanisms together with membrane contact conditions as criteria, there are six potential extraction mechanism regimes identified as: (a) no extraction, (b) pure evaporation, (c) pure bubble extraction, (d) bubble extraction with partial liquid blockage, (e) bubble extraction with evaporation, and (f) liquid breakthrough. The physical conditions for each regime are summarized in Table 2 where the characteristic of each regime are described as below: 

a) **No extraction** is when the pressure differential across the membrane is not sufficient to initiate either bubble extraction or evaporation.

b) **Pure evaporation** is when the extraction surface is in full contact only with liquid which evaporates such that vapor flows through the membrane.

c) **Pure bubble extraction** is when the vapor phase is in full contact with the membrane and is extracted through the membrane.

d) **Bubble extraction with partial liquid blockage** is when a fraction of the extraction area is blocked by liquid and vapor is extracted.

e) **Bubble extraction with evaporation** is similar to bubble extraction with partial liquid blockage, however, the liquid that blocks the vapor also evaporates, resulting in both modes of vapor extraction.

f) **Liquid breakthrough** is when the pressure difference across the membrane is greater than the breakthrough pressure and the liquid phase leaks into or through the membrane pores.

It should be noted that regime (d) may only occur for liquid-gas flow, not during boiling, since the liquid phase during boiling will be near saturated conditions and an applied pressure differential across the membrane would cause evaporation, regime (e).

The extraction of vapor from the flow most likely would cause change to the flow conditions resulting in a change in phenomenological conditions of the extraction mechanism regime along the flow. As a result, extraction mechanism regimes should, in general, be seen as a local condition along the flow. For example, a high temperature single-phase flow enters a channel. Liquid in contact with membrane may evaporate, resulting pure evaporation, regime (b). As evaporation takes place, the liquid temperature near the membrane decreases along the flow which may suppress evaporation, resulting in no extraction, regime (a).

### EXTRACITION MECHANISM REGIME TRANSITION

The development of extraction mechanism regime transition criteria is based on modeling the transition of both the membrane contact phase and membrane transport mechanism. The regimes are shown in Table 2 along with the phenomenological conditions associated with the membrane contact phase and transport mechanism. The transition criteria are discussed in detail below.

<table>
<thead>
<tr>
<th>Regimes</th>
<th>Phenomenological conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) No extraction</td>
<td>Liquid or vapor</td>
</tr>
<tr>
<td>(b) Pure evaporation</td>
<td>Liquid</td>
</tr>
<tr>
<td>(c) Pure bubble extraction</td>
<td>Vapor</td>
</tr>
<tr>
<td>(d) Bubble extraction with partial liquid blockage</td>
<td>Both</td>
</tr>
<tr>
<td>(e) Bubble extraction with evaporation</td>
<td>Both</td>
</tr>
<tr>
<td>(f) Liquid breakthrough</td>
<td>Liquid or partial vapor</td>
</tr>
</tbody>
</table>

### Membrane Contact Phase

Although the hydrophobic nature of the membrane generally repels the liquid phase, the membrane is not expected to be totally dry during two-phase flow. Consequently, the membrane can be locally dry or wet. Some regions could have a mixture of both phases. Two criteria are used to separate these three membrane situations: (i) liquid film formation, and (ii) stratification to an intermittent flow regime. For liquid to be the only phase in contact with the membrane, there must be a liquid film formation on the membrane. To separate between vapor only and mixed phases in contact with the membrane, the contact characteristics are assumed to be related to the two-phase flow regime of the fluid inside the channel. In other words, the vapor phase is likely to be the only phase in contact with membrane for stratified flow, where liquid and vapor are completely separated. On the other hand, a mix of both phases tends to occur for an intermittent flow. Although stratified flow is rarely found in most microscale flow boiling applications, stratified flow may be found in flow boiling with in-situ vapor extraction applications. This is because at least one wall of the channel is formed by a hydrophobic porous membrane, with surface tension forces favoring vapor contact. The experiment observations by David et al. [25] support this hypothesis that the stratified flow is reported to be a dominated flow type in low velocity situations. The conditions for liquid film formation and transition from stratified to intermittent flows are discussed next.

#### Liquid film formation

The liquid film formation condition is evaluated based on the fact that the dynamic contact angle decreases with increasing bubble velocity. As the dynamic contact angle approaches zero, the bubble critical velocities corresponding to liquid film formation is estimated based on criteria given by de Gennes et al. [32]:

\[
u_{\text{crit}} = \frac{1}{9 \sqrt{3}} \frac{\sigma \mu_\text{L}}{a \rho \mu \text{mem}}
\] (3)
where $\theta_{c,\text{mem}}$ is the membrane contact angle and $a$ is a nondimensional parameter with values suggest between 15-20. A liquid film forms when the bubble travels faster than this critical velocity ($u_{\text{bub}} > u_{\text{crit}}$). For simplicity, the bubble velocity may be estimated as the vapor superficial velocity, $j_v$. Using this, and expressing this in dimensionless form, the film formation criterion can be expressed as:

$$Ca_c > \frac{1}{9^{\frac{1}{3}}} \frac{\theta_{c,\text{mem}}}{a}$$

(4)

where $Ca_c = \frac{\mu_j j_v}{\sigma}$. A liquid film formation map for values of $a$ of 15 and 20, based on Eq. (4) is shown in Figure 2, where the region on the left hand side of the line indicates the existence of liquid film on the membrane.

Once a film is formed, it may rupture. Assuming that the film starts to rupture when its thickness is on the same order as the surface roughness, the film rupture condition in terms of volume of liquid is estimated as:

$$V_l < \varphi_w \delta_c L$$

(5)

or in terms of vapor volume as:

$$A_L - V_l < \varphi_w \delta_c L$$

(6)

where $\delta_c$ is the channel surface roughness and $\varphi_w$ is the wetted perimeter. Dividing by $A_L$:

$$1 - \alpha < \left(\frac{\varphi_w \delta_c}{A_L}\right)$$

(7)

Rearranging and using hydraulic diameter, $D_h = 4A_L/\varphi_w$, the criterion for film rupture may be roughly estimated in terms of flow void fraction as:

$$\alpha > 1 - 4\delta_c / D_h$$

(8)

The void fraction, $\alpha$, can be estimated using one of several models, such as the model developed for annular flow by Zivi [33]:

$$\alpha = \left[1 + \left(\frac{1}{x}\right)^{2/3}\right]^{-1}$$

(9)

By combining Eqs. (8) and (9), the film rupture map, given in Figure 3, shows the film rupture region on the upper right hand side of the demarcation line. Both film formation and rupture maps can be used to estimate the existence of liquid film on the membrane. For example, for flow boiling with constant mass flux, a film may form with increasing quality due to flow acceleration resulting from phase change. However, as the quality further increases along the flow the liquid phase may be insufficient to form a film.

Stratified to intermittent flow regime transition

The criterion for two-phase flow regime transition from stratified to intermittent flows can be used to identify the transition from vapor only to a mixture of two phases in contact with the membrane. The following assumes the membrane wall is on the top of the channel. To illustrate the transition, the criterion developed by Taitel and Dukler [26] is used in this study. This criterion is developed based on the assumption that the lift, caused by vapor acceleration over a liquid-vapor wave interface, disturbs the liquid-vapor interface of stratified flow leading to the rapid growth of interfacial waves which block the vapor flow path. There are two conditions to be satisfied for the transition from stratified to intermittent flow. First, the lift, due to the decrease of pressure in the accelerating vapor over the wave interface owing to the Bernoulli effect, overcomes the gravitation force. Second, the liquid phase flow must be sufficient to maintain slug flow, otherwise annular flow will take place. It should be noted that although Taitel and Dukler [26] developed the transition criteria in dimensionless form, it is modeled specifically for two-phase flow in a circular tube. To use those criteria for other channel geometries such as rectangular channel, which is common for microscale application, modification of those models are required.

By considering a finite solitary wave, the vapor velocity, $u_v$, condition for rapid wave growth inside the channel is evaluated as [26]:

$$u_v > C_u \left(\frac{\rho_v - \rho_l}{\rho_v} g \cos \beta \frac{A_{dx}}{dA_{dx}/dH_t}\right)^{1/2}$$

(10)
where $\beta$ is the channel inclination angle relative to gravity and $C_{w} = A_{c} / A_{v}$, depends on the size of the wave and ranges between 0 and 1, with $A_{c}$ and $A_{v}$ representing the cross-sectional area of vapor flow and the finite wave peak area, respectively. The above relationship can be rewritten as a function of modified Froude number, $Fr^{*}$, for a general channel geometry as:

$$Fr^{*} > \sqrt{\frac{C_{w}}{S}} \left( \frac{A_{c}}{A_{v}} \right) \frac{A_{c} / H}{dA_{c} / dH}, \quad (11)$$

where $Fr^{*}$ is defined as:

$$Fr^{*} = \frac{\rho_{v} - \rho_{l}}{\rho_{l} g \cos \beta} \sqrt{\frac{j_{c}}{A_{c}}} \quad (12)$$

For rectangular channel, Eq. (11) is rewritten as:

$$Fr^{*} > C_{w} \left( 1 - H_{l} / H \right)^{3/2}, \quad (13)$$

assuming a wave extends across the entire channel. For simplicity, $C_{w}$ is estimated by Taitel and Dukler [26] as:

$$C_{w} \approx 1 - H_{l} / H \quad (14)$$

where $H_{l} / H$ is a normalized liquid height for equilibrium stratified flow. Using this estimated value of $C_{w}$, the criterion for rapid wave growth in rectangular channel becomes:

$$Fr^{*} > \left( 1 - H_{l} / H \right)^{3/2} \quad (15)$$

For a circular tube, $Fr^{*}$ can be evaluated as a function of $H_{l} / D$. Based on the equilibrium stratified flow condition, provided by Taitel and Dukler [26], $H_{l} / D$ is a unique function of the Lockhart-Martinelli parameter, $X_{2}$, denoted as:

$$X_{2} = \left( \frac{(dP/dz)_{l}}{(dP/dz)_{v}} \right), \quad (16)$$

and $Y$ is the dimensionless parameter that represents the ratio of gravitational force in the flow direction to the pressure drop of vapor phase, denoted as:

$$Y = \left( \frac{\rho_{v} - \rho_{l}}{g \sin \beta} \right) \frac{(dP/dz)_{l}}{(dP/dz)_{v}} \quad (17)$$

Note that for horizontal flow, $Y = 0$.

The condition for an equilibrium stratified flow was developed by considering the momentum equation of each phase for an equilibrium stratified flow and then equating the pressure drop terms of both equations. Using this condition, the criterion for rapid wave growth in circular tube is written as a function of $Fr^{*}$, $X_{2}$ and $Y$. By following this approach, the condition for rapid wave growth in other channel geometries can be determined. The condition for equilibrium stratified flow as modified for any channel geometry is:

$$X_{2} \left[ \left( \frac{S_{c}}{S} \right)^{n} \left( \frac{A_{c}}{A_{v}} \right)^{m} \right] - Y$$

$$- \left[ \left( \frac{S_{c}}{S} \right)^{n} \left( \frac{A_{c}}{A_{v}} \right)^{m} \left( \frac{S_{c}}{S} \right) \left( \frac{A_{c}}{A_{v}} \right) \right] = 0 \quad (18)$$

where $S$ is the contact surface area of the fluid per unit length, and the exponents $m$ and $n$ are the exponents of the Reynolds number in the Blasius equation for vapor and liquid phases, respectively, which are equal to 1.0 for laminar flow and 0.2 for turbulent flow. Note that for laminar-laminar or turbulent-turbulent flow boiling $(n = m)$, $X_{2}$ can be rewritten as a function of quality, $x$, as:

$$X_{2} = \left( \frac{\mu_{l}}{\mu_{c}} \right)^{x} \left( \frac{1 - x}{x} \right)^{2-n} \frac{V_{l}}{V_{c}} \quad (19)$$

The cross-sectional area, $A_{c}$, and the contact surface area per unit length, $S$, are different for each channel geometry, as shown in Figure 4. For a rectangular channel, the ratios of $S$ and $A_{c}$, in Eq. (18), are evaluated as a function of $H_{l} / H$ and channel aspect ratio, $\alpha_{c}$, as:

$$\frac{A}{A_{l}} = (H_{l} / H)^{-1} \quad (20)$$

$$\frac{A}{A_{l}} = (1 - H_{l} / H)^{-1} \quad (21)$$

$$\frac{S_{l}}{S} = \frac{2}{2 (1 + \alpha_{c})} \quad (22)$$

$$\frac{S_{c} + S_{l}}{S} = 1 - H_{l} / H \quad (23)$$

$$\frac{S_{c}}{S} = \frac{\alpha_{c}}{2 (1 + \alpha_{c})} \quad (24)$$

where $\alpha_{c}$ is channel aspect ratio, denoted as:

$$\alpha_{c} = W / H \quad (25)$$

Based on Eqs. (18)-(25), the equilibrium stratified flow condition for rectangular channels can be written as a function of $X_{2}$, $Y$ and $\alpha_{c}$. Consequently, the condition for rapid wave growth in a rectangular channel is evaluated as a function of $Fr^{*}$, $\alpha_{c}$, $X_{2}$ and $Y$.

As previously mentioned, in addition to rapid wave growth, the liquid level must be sufficient to form a liquid slug. Taitel and Dukler [26] suggested that the transition between intermittent and annular flow takes place at:

$$H_{l} / H > 0.5 \quad (26)$$
while in the later work by Barnea et al. [34] it is recommended that the criterion for the transition is:

$$H_f/H > 0.35$$  \hspace{1cm} (27)

This latter criterion can be used together with the condition for equilibrium stratified flow, Eqs. (18), and (20)-(24), to form a relationship among $\alpha_c$, $X^2$, and $Y$.

It should be noted that Barnea et al. [27] suggests that the rapid wave growth and sufficient liquid level conditions, developed by Taitel and Dukler [26], is not sufficient to be applied to small channels. An additional criterion is required to account for surface tension forces that pull liquid to the channel walls. However, the additional criterion is not used in this study because the membrane used in vapor extraction application is usually hydrophobic. Thereby, surface tension forces that pull liquid upward onto a membrane will be minimal.

Based on rapid wave growth and liquid level conditions, the membrane contact phase can be determined. Figure 5 shows the membrane contact phase for horizontal two-phase laminar-laminar flow in a rectangular channel without a liquid film formation using the liquid level criterion from Barnea et al. [34]. The region on the right of the line represents the intermittent flow regime which corresponds to mixed phases in contact with the membrane. The sudden change in slope near $X^2 = 1$ is due to the change from the rapid wave growth condition to the sufficient liquid level condition. It shows that for low value of $X^2$, i.e. high quality, the condition is independent of $Fr^*$. This is because the liquid phase is not sufficient to form on the membrane. It also shows that the vapor only region extends with increasing channel aspect ratio. This is due to the fact that as the aspect ratio increases, the channel is wider, and thereby results in a larger contact area for the vapor phase. Therefore, the required quality to match the pressure drop of both phases in channel is less, i.e. higher value of $X^2$.

A dimensional membrane contact phase map can be developed by combining conditions for liquid film formation with stratified to intermittent flow transition. Two examples of the dimensional membrane contact phase map are shown in Figure 6. Lines A, B, C and D are based on film formation, Eq.(4), film rupture criteria, Eq. (8), rapid wave growth, Eq. (15), and sufficient liquid level, Eq. (27), respectively. It is implied from Figure 6(a) that full extraction is hard to achieve since near zero quality there is a "mixed phases" region which has the potential to reduce the effective bubble extraction area. Since extracting vapor decreases the available quality within the channel, the membrane contact phase may change from "vapor only" to "mixed phases" near a quality of 0.015. This supports the observation by several studies [20-21] that vapor extraction from two-phase flow is less effective compared with single-phase membrane transport in some flow conditions. It is proposed that this membrane contact phase map can be used as a basis to develop models for vapor extraction from two-phase flow since vapor extraction from two-phase flow should be related to the area of each phase in contact with the membrane.

**Membrane Transport Mechanism**

As previously discussed and summarized in Table 1, the
conditions to initiate bubble extraction and evaporation are that the bubble pressure and local saturation pressures be greater than the extraction pressure to drive the vapor across the membrane. The bubble pressure, \( P_{\text{bub}} \), is expected to be somewhat higher than the local channel pressure due to the curvature of the bubble. For simplicity, this difference in pressure is assumed negligible. Therefore, the condition for bubble extraction becomes:

\[
P_{\text{chan}} > P_{\text{ex}}
\]

The upper limit on the differential pressure across the membrane is based on the breakthrough pressure. It is expected that the breakthrough pressure may be varied with temperature as it relies on the surface tension force. Assuming a nearly linear variation of breakthrough pressure with surface tension, temperature variations of the breakthrough condition may be written in term of the surface tension ratio versus temperature and the breakthrough pressure at a specific temperature, such as:

\[
P_{\text{chan}} < P_{\text{chan}} - \sigma \frac{L}{T} \Delta P_{\text{break}} |_{T_c}
\]

Using the conditions for evaporation, bubble extraction, and breakthrough, the membrane transport mechanism can be determined based on channel pressure, membrane temperature and extraction pressure. For example, a membrane transport mechanism map for water at 100 kPa-a and membrane breakthrough pressure at 25°C of 70 kPa is shown in Figure 7 as a function of extraction pressure and membrane temperature, for evaporation, bubble extraction and breakthrough, respectively. Note that the membrane transport mechanisms shown here are possible transport modes. It may be needed to also consider the membrane contact phase and thus the hydrodynamics to get the exact transport mechanism. For example, although the region at 75°C with 50 kPa-a extraction pressure in Figure 7 is shown as "Evaporation/Bubble extraction", only evaporation would occurs if a liquid film is formed on the membrane.

**EXTRACTION FLOW REGIMES**

In the previous section, the extraction regime is characterized based on the condition of the fluid near the membrane which can be seen as the local condition for extraction. Globally, as vapor extraction affects the flow boiling, flow conditions change and thereby so does the vapor extraction conditions. In other words, vapor extraction and flow boiling conditions are coupled. In this section, vapor extraction affected by flow boiling is characterized. It should be noted that the extraction flow regimes are considered only when there is a vapor mass extraction without liquid breakthrough, i.e. the extraction mechanism regimes (b) to (e) shown in Table 2.

The following six potential extraction flow regimes are characterized based on the amount of vapor leaving the outlet of the channel, the boiling condition, and flow stability. The identified regimes are: (i) single-phase evaporation, (ii) two-phase evaporation – bubble collapse, (iii) full extraction - stable, (iv) full extraction - unstable, (v) partial extraction – stable and (iv) partial extraction – unstable. The phenomenological conditions of each regime are summarized in Table 3 where the characteristics of each regime are described as below:

i. **Single-phase evaporation** occurs when there is no vapor generation within the channel, and evaporation through the membrane results in vapor extraction.

ii. **Two-phase evaporation - bubble collapse** occurs when bubbles generated during subcooled boiling, condense in the main stream flow rather than being extracted, so evaporation occurs at the membrane.

iii. **Full extraction - stable** occurs when all generated vapor is extracted and the flow is stable.

iv. **Full extraction - unstable** is similar to regime (iii), however, with all generated vapor extracted the vapor extraction is not sufficient to stabilize the flow.

v. **Partial extraction - stable** represents the case when some generated vapor is extracted, leaving excess vapor exiting...
through the channel outlet while the vapor extraction is sufficient to suppress the flow instability.

vi. Partial extraction - unstable is similar to regime (v) but bubbles generation exceeds the rate of vapor extraction such that flow is unstable.

**EXTRACTION FLOW REGIME TRANSITION**

To identify the extraction mechanism regime transition, the physical conditions related to the extraction flow regimes, which are outlet quality, boiling condition and flow stability, are analyzed below. The extraction flow regime is then identified by matching the physical conditions with the phenomenological conditions of extraction flow regime, summarized in Table 3.

**Outlet Quality**

The quality at the channel outlet can be evaluated by considering conservation relationships applied to the entire channel as shown in Figure 8. Combining conservation of mass and energy and neglecting kinetic energy terms results in:

\[ q + \dot{m}_{in} (i_{in} - i_{out}) = \dot{m}_{extr} (i_{extr} - i_{out}) \]  

(30)

The conservation equation for inlet subcooled liquid becomes:

\[ \frac{(i_{out} - i_{i})}{i_{i}} = \frac{q - \dot{m}_{in} c_{p,l} \Delta T_{sub,in} - \dot{m}_{extr} [i_{h} - (i_{out} - i_{i})]}{i_{h}} \]  

(31)

or

\[ \frac{(i_{out} - i_{i})}{i_{i}} = \frac{q - \dot{m}_{in} c_{p,l} \Delta T_{sub,in} - \dot{m}_{extr} [i_{h} - (i_{out} - i_{i})]}{i_{h}} \]  

(32)

Here it is assumed that \( c_{p,l} \) is constant along the channel and \( i_{extr} \approx i_{i} \). Based on the definition of thermodynamic equilibrium quality where:

\[ x_{out} = \frac{(i_{out} - i_{i})}{i_{i}} \]  

(33)

the quality at the channel outlet becomes:

\[ \frac{q}{\dot{m}_{in} c_{p,l} \Delta T_{sub,in} - \dot{m}_{extr} [i_{h} - (i_{out} - i_{i})]} = \frac{i_{h}}{i_{i}} \]  

(34)

The relationship among the variables in Eq. (35) is shown in Figure 9. The quality at the channel outlet decreases with increasing \( N_{extr} \), as both energy and mass are extracted through the membrane. Note that vapor extraction can decrease the quality at the outlet to be negative, i.e. the outlet is a subcooled liquid, when the extraction mass flow rate is greater than generated vapor due to excessive evaporation.

**Boiling Condition**

Incipience of boiling occurs when the wall superheat, \( \Delta T_{sat} = T_{w} - T_{sat} \), is sufficient such that the local saturation pressure exceeds the combined static and surface tension induced pressures. Many studies have found that this wall superheat requirement depends on the size of active nucleation sites. For example, the nucleation criterion developed by Hsu [35] shows a range of active nucleation size as a function of wall superheat as:

\[ x_{out} = \frac{x_{out}}{N_{extr}} \]  

(35)

where the extraction number, \( N_{extr} \), represents the ratio of the extraction and inlet mass flow rates, and \( x_{out}^{*} \) represent the quality at the channel outlet that would occur without vapor extraction (\( \dot{m}_{extr} = 0 \)), defined as:

\[ x_{out}^{*} = \frac{q}{\dot{m}_{in} c_{p,l} \Delta T_{sub,in}} \]  

(36)

It should be noted that \( x_{out}^{*} \) can be rewritten in term of the modified Boiling number, \( Bo^{*} = q m_{in}^{*} \), and Jacob number, \( Ja^{*} = \rho_{v} c_{p,v} \Delta T_{sub,in} \), as:

\[ x_{out}^{*} = Bo^{*} \]  

(37)

The relationship among the variables in Eq. (35) is shown in Figure 9. The quality at the channel outlet decreases with increasing \( N_{extr} \), as both energy and mass are extracted through the membrane. Note that vapor extraction can decrease the quality at the outlet to be negative, i.e. the outlet is a subcooled liquid, when the extraction mass flow rate is greater than generated vapor \( N_{extr} > x_{out}^{*} \) due to excessive evaporation.
\[
\{ r_{\text{on}}, r_{\text{off}} \} \Rightarrow \frac{\delta \sin \theta_{w}}{2(1 + \cos \theta_{w})} \left( \frac{\Delta T_{\text{sat,ONB}}}{\Delta T_{\text{sat,ONB}} + \Delta T_{\text{sub,ONB}}} \right) \]

(38)

where \( \theta_{w} \) is a wall contact angle and \( \delta \) is estimated as \( k_{l}/\rho_{l} \).

Generally, for a system with sufficient active nucleation sites, the minimum required wall superheat for the incipience of boiling can be simplified as:

\[
\Delta T_{\text{sat,ONB}} = \frac{8C_{b} \sigma T_{w} q_{*}}{\rho_{l} i_{l}} \]

(39)

where \( C_{b} \) was initially proposed by Hsu [35] for pool boiling as:

\[
C_{b} = 1 + \cos \theta_{w} \]

(40)

Several investigators modified this minimum required wall superheat for boiling incipience by modifying variable \( C_{b} \). A few examples of variable \( C_{b} \) for the boiling incipience models are shown in Table 4.

To determine whether boiling occurs within the channel, the incipience of boiling criterion may be written in terms of quality which can be easily compared with the quality at the channel outlet, given in the previous section as Eq. (35). Using definitions of the wall superheat and subcooling, \( \Delta T_{\text{sub}} = T_{\text{sat}} - T_{w} \), then:

\[
\Delta T_{\text{sub}} = \frac{q_{*}}{h_{b}} - \Delta T_{\text{sat}} \]

(41)

Assuming that the fluid is entirely liquid from inlet to the point of the onset of nucleate boiling, the heat transfer coefficient is estimated as all-liquid heat transfer coefficient, \( h_{b} \), where:

\[
h_{b} = \frac{N_{u, b} k_{l}}{D_{b}} \]

(42)

At the location where boiling starts, Eq. (41) is rewritten as:

\[
\Delta T_{\text{sub,ONB}} = \frac{q_{*}}{h_{b}} - \Delta T_{\text{sat,ONB}} \]

(43)

Table 4. Variable \( C_{b} \) for boiling incipience models

<table>
<thead>
<tr>
<th>Author and (Model)</th>
<th>( C_{b} )</th>
<th>Eq.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sato and Matsumura [36] (Pool boiling)</td>
<td>1</td>
<td>(44)</td>
</tr>
<tr>
<td>Ghaasai and Chedester [37] (Microchannel)</td>
<td>( C_{b} = 22.2 \sqrt{\frac{k_{l} - \rho_{l} i_{l}}{\sigma \left</td>
<td>\frac{\delta}{\rho_{l} i_{l} R} \right</td>
</tr>
<tr>
<td>and ( R = \left[ \frac{2\sigma T_{w} v_{l} k_{l}}{q_{*} i_{l}} \right]^{1/2} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kandlikar [38] (Microchannel)</td>
<td>1.1</td>
<td>(46)</td>
</tr>
</tbody>
</table>

Multiplying this by \( c_{p,l} \), and introducing the quality in the liquid region as:

\[
x = i - i_{l} = -\left( \frac{c_{p,l} \Delta T_{\text{sub}}}{i_{l}} \right) \]

results in:

\[
x_{\text{ONB}} = \frac{c_{p,l}}{i_{l}} \left( \Delta T_{\text{sat,ONB}} - \frac{q_{*}}{h_{b}} \right) \]

(51)

For boiling to occur within the channel, the quality at the channel outlet must be greater than the quality for the onset of nucleate boiling, i.e. \( x_{\text{out}} \geq x_{\text{ONB}} \). Using the relationship among \( x_{\text{out}}, x_{\text{sat}}^{*} \) and \( N_{\text{extr}} \), presented in Eq. (35), the boiling condition can be determined in term of \( x_{\text{sat}}^{*} \) and \( N_{\text{extr}} \). The criterions of each boiling condition are summarized in Table 5. An example of the boiling map is generated by using the minimum wall superheat correlation by Hsu [35] and is shown in Figure 10.

Figure 10. Example of a boiling map for flow in 500 \( \mu \)m \times 500 \( \mu \)m channel with length of 50 mm and contact angle of 53° where inlet mass flux and subcooling are 400 kg/m2s and 10°C respectively.
Stability

The stability criterion applied to this study is based on whether vapor experiences reverse, or back, flow into the inlet chamber. The criterion based on the model proposed by Salakij et al. [12-13], which was developed for flow boiling in a diverging channel with vapor extraction, is used in this study. The stability parameter, St, that represents the ratio of backward to forward forces acting on the upstream side of the liquid-vapor interface of the expanding bubble, is expressed as:

\[
St = \frac{\sqrt{\frac{\left(q - \dot{m}_{\text{extr},h}l_i\right)^2}{\rho_i A_{\text{ch,in}}^2 + \frac{1}{A_{\text{ch,out}}}}} \left[\frac{G_{\text{in}}^2 A_{\text{ch,in}}^2 + \sigma \varphi_{\text{v,in}}}{\rho_i}\right]}{rac{G_{\text{in}}^2 A_{\text{ch,in}}^2 + \sigma \varphi_{\text{v,in}}}{\rho_i}}
\]  

(52)

where subscript 1 and 2 represent the location of upstream and downstream sides of an expanding bubble, respectively. The transition from stable to unstable flow occurs when \(St = 1\) at the extreme case where an expanding bubble fills the channel and barely reverses into the inlet chamber such that \(A_{\text{heat,bub}} = A_{\text{heat,ch,in}}, A_{\text{extr,bub}} = A_{\text{extr,ch,in}}, A_{\text{v,1}} = A_{\text{in}}\) and \(A_{\text{v,2}} = A_{\text{out}}\). It should be noted that this model does not account for the instability due to insufficient nucleation sites. Since the half-diverging angle of the channel, \(\theta_d\), is usually relatively small on the order of \(1^\circ-3^\circ\), the term \(\cos \theta_d\) may be approximated as 1. In this study, the criterion for stable flow (\(St < 1\)) is expressed as:

\[
\rho_i \left(q - \dot{m}_{\text{extr},h}l_i\right)^2 \left[\frac{1}{A_{\text{ch,in}}^2 + \frac{1}{A_{\text{ch,out}}}}\right] < \left[\frac{G_{\text{in}}^2 A_{\text{ch,in}}^2 + \sigma \varphi_{\text{v,in}}}{\rho_i}\right]
\]  

(53)

By dividing this by \(G_{\text{in}}^2 A_{\text{ch,in}}^2 / \rho_i\) and using and the inlet hydraulic diameter, \(D_{\text{h,in}} = 4A_{\text{ch,in}} / \varphi_{\text{v,in}}\), Eq. (53) becomes:

\[
\left(\frac{q - \dot{m}_{\text{extr},h}l_i}{G_{\text{in}}^2 A_{\text{ch,in}}^2 / \varphi_{\text{v,in}}}\right)^2 < \left[\frac{\rho_i}{\rho_i} \left[1 + \frac{4\rho_i \sigma}{G_{\text{in}}^2 D_{\text{h,in}}}\right]\right] \left[\frac{\rho_i}{\rho_i} \left[1 + \frac{4\rho_i \sigma}{G_{\text{in}}^2 D_{\text{h,in}}}\right]\right] + \frac{\dot{m}_{\text{extr},i}}{\dot{m}_{\text{extr},h}}
\]  

(54)

which can be rearranging as:

\[
\frac{q}{\dot{m}_{\text{extr},h}l_i} < 1 + \frac{A_{\text{ch,out}}}{A_{\text{ch,in}}} \left[\frac{\rho_i}{\rho_i} \left[1 + \frac{4\rho_i \sigma}{G_{\text{in}}^2 D_{\text{h,in}}}\right]\right]^{1/2} + \frac{\dot{m}_{\text{extr},i}}{\dot{m}_{\text{extr},h}}
\]  

(55)

In dimensionless form, the criterion for stable flow is expressed in terms of the extraction number, \(N_{\text{extr}}\), the modified boiling number, \(Bo^*_m\), and Weber number, \(We_{\text{in}}\), as:

\[
Bo^*_m < 1 + \frac{A_{\text{ch,out}}}{A_{\text{ch,in}}} \left[\frac{\rho_i}{\rho_i} \left[1 + \frac{4\rho_i \sigma}{We_{\text{in}}}\right]\right]^{1/2} + N_{\text{extr}} \frac{i_j}{i_j}
\]  

(56)

where Weber number is defined as \(We_{\text{in}} = \frac{G_{\text{in}}^2 D_{\text{h,in}}}{\rho_i \sigma}\).

The stability map for water at 100°C is shown in Figure 11 where the left hand side of the line is the stable region. Figure 11(a) shows that the stability region for a uniform cross-sectional channel is the smallest when \(We_{\text{in}}\) approaches infinity which represents negligible surface tension effects that suppress the instability compared with the inertia forces. This case is chosen to show the effect of varying cross-sectional area ratio, as shown in Figure 11(b). In general, the stability region can be extended by increasing the cross-sectional area ratio \(\left(A_{\text{ch,in}} / A_{\text{ch,in}}\right)\) and \(N_{\text{extr}}\), and decreasing \(We_{\text{in}}\). This supports the results from several investigators [5, 8-10] that expanding the channel improves flow stability.

DISCUSSIONS

Ideally the completed extraction mechanism and extraction flow regime maps should be developed in form of an independent single map. However, it may not be practical to combine all individual criterion together in this case because there are a large number of independent variables to be included. For example, to get the complete single dimensional extraction mechanism map for a specific fluid flow in a specific channel geometry requires four independent variables: either \((P_{\text{extr}}, T_{\text{mem}}, G, x)\) or \((P_{\text{extr}}, T_{\text{mem}}, j_l, j_f)\). As previously suggested, it would be more practical to use individual maps to identify physical conditions of the regime, and then combine the known predicted conditions to identify the regime.

The regime transition criteria developed in this study are fully predictive based on physical concepts. The important assumptions used in the development are listed below:
Film rupture when film thickness is in the same order as surface roughness.

Membrane contact phase is strongly dependent on hydrodynamics of the flow where stratified flow and intermittent flows are related to vapor only and mixed phases contact, respectively.

Transition from stratified to intermittent flow is caused by rapid wave growth due to the decreasing in pressure of vapor flow, and liquid phase must be sufficient to form slugs. (Taitel and Dukler [26])

Membrane hydrophobicity prevents the surface tension force from pulling liquid to the wall to form slugs.

Negligible pressure differences occur between pressure inside the bubble and surrounding liquid.

For extraction flow analysis, $c_{p,i}$ are assumed to be constant along the flow.

Enthalpy of the extracted vapor is estimated as the enthalpy of superheated vapor inside the extraction chamber.

Most of the assumptions and models used in this study have been validated and shown to be reliable for specific conditions in other types of applications. It is expected that to apply these models with reasonable adaptation to in-situ vapor extraction application, further modification is required. The models for regime transition criteria in this work are developed such that they can be adjusted easily. For example, dimensionless coefficients $C_w$ and $C_b$ for rapid wave growth, and onset of nucleate boiling criteria, respectively, can be modified to capture other effects.

To validate the assumptions and models for extraction mechanism regime transition, flow visualization on both sides of the membrane is required such that the membrane contact phase and breakthrough can be observed. Because an extraction mechanism regime depends on the local condition, the test section should be small and short such that quality of flow boiling does not vary significantly within the observed section. The membrane surface temperature has to be measureable or, even better, controllable. Also, it is important to be able to have a precise quantitative measurement of film thickness that forms on the membrane and channel walls as well as surface roughness and contact angle of both membrane and channel walls. For extraction flow regime transition, precise measurements of mass flow rate, fluid temperature, pressure and quality at inlet, outlet and extraction chamber are required as well as flow visualization to identify boiling mechanism and flow instability.

CONCLUSIONS

A systematic development of transition criteria for extraction mechanism and extraction flow regimes has been presented. All of the transition criteria are developed on a basis which can be easily modified to account for additional effects. Although the validation of the extraction mechanism and extraction flow regime transition criteria were not presented here, most models and assumptions have been validated in part in other applications in the literature. The methodology to validate transition models has been proposed and recommended. Examples of membrane contact phase, possibly extraction mechanism, boiling and stability maps, and effect of extraction on outlet quality are shown as tools to identify extraction regimes. The membrane contact phase map helps explain that vapor extraction from two-phase flow is less effective in low quality conditions compared with single-phase membrane transport due to the reduced complex nature of the vapor contact area.

NOMENCLATURE

$A$ Area

$Bo^*$ Modified Boiling number, $Bo^* = \frac{q}{\dot{m}_{i,v}}$

$Ca_v$ Capillary number, $Ca_v = \frac{\mu_i \dot{j}_v}{\sigma}$

$C_b$ Dimensionless parameter for minimum wall superheat requirement

$C_w$ Rapid wave growth factor

$c_p$ Specific heat

$\Delta d_p$ Equivalent membrane pore size

$D_h$ Hydraulic diameter

$Fr^*$ Modified Froude number, $Fr^* = \frac{\rho_i - \rho_v \sqrt{gH \cos \alpha}}{\sqrt{\dot{j}_v}}$

$g$ Acceleration due to gravity

$G$ Mass flux

$H$ Channel depth

$H_l$ Liquid level height

$h$ Heat transfer coefficient

$i$ Enthalpy

$i_v$ Heat of vaporization

$Ja$ Jacob number, $Ja = \frac{\rho_i c_p \Delta T_{ub}}{\dot{m}_v i_v}$

$j$ Superficial velocity

$k$ Thermal conductivity

$m$ Mass flow rate

$N_{extr}$ Extraction number, $N_{extr} = \dot{m}_{extr}/\dot{m}_m$

$Nu$ Nusselt number

$P_{extr}$ Extraction absolute pressure

$\phi_w$ Wetted perimeter

$q$ Heat input rate

$q''$ Heat flux

$S$ Contact surface per unit length

$St$ Stability parameter

$T$ Temperature

$u$ Velocity

$v$ Specific volume

$W$ Channel width

$We$ Weber number, $We = \frac{G^2 D_h}{\rho \sigma}$
\( X^2 \)  
Lockhart-Martinelli parameter

\( x \)  
Thermodynamic equivalent quality

\( x_{\text{out}} \)  
Ideal exit quality without vapor extraction,

\[
x_{\text{out}} = \frac{q}{m_{\text{in}}} - c_p^v \Delta T_{\text{sub,in}}
\]

\( Y \)  
Dimensionless parameter presented in [26],

\[
y = \frac{(\rho_1 - \rho_f) g \sin \beta}{(dP/dz)_{|z}}
\]

\( \alpha \)  
Void fraction

\( \alpha_c \)  
Channel aspect ratio, \( \alpha_c = W/H \)

\( \beta \)  
Channel inclination angle

\( \delta_c \)  
Surface roughness

\( \delta_i \)  
Thermal boundary thickness, \( \delta_i = k_i/h_i \)

\( \Delta P_{\text{erv}} \)  
Extraction pressure differential

\( \Delta T_{\text{sat}} \)  
Wall superheat,

\[
\Delta T_{\text{sat}} = T_{s} - T_{\text{sat}}
\]

\( \Delta T_{\text{sub}} \)  
Subcooling,

\[
\Delta T_{\text{sub}} = T_{\text{sat}} - T_{b}
\]

\( \theta_c \)  
Contact angle

\( \theta_d \)  
Half-diverging angle

\( \kappa \)  
Specific permeability

\( \mu \)  
Dynamic viscosity

\( \nu \)  
Kinematic viscosity

\( \rho \)  
Density

\( \sigma \)  
Surface tension

**Greek**

**Subscripts**

\( b \)  
Bulk

\( bub \)  
Bubble

\( c \)  
Cross-sectional

\( extr \)  
Extraction

\( heat \)  
Heated

\( i \)  
Liquid-vapor interface

\( in \)  
Inlet

\( l \)  
Liquid phase

\( lo \)  
All-liquid

\( mem \)  
Membrane

\( ONB \)  
Onset of nucleate boiling

\( out \)  
Outlet

\( sat \)  
Saturation

\( v \)  
Vapor phase

\( w \)  
Wall

**ACKNOWLEDGEMENT**

The authors acknowledge the financial support of this work from Office of Naval Research (N00014-09-1-1079, Dr. Mark Spector, program manager).

**REFERENCES**


