Modeling in situ vapor extraction during convective boiling in fractal-like branching microchannel networks

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1. Introduction

An effective heat sink should achieve a high heat removal rate, maintain a low and relatively uniform and stable temperature and minimize the overall pressure loss and/or flow power requirements. The advantages of using microchannels are higher surface area per unit volume, larger heat transfer coefficients, low flow rate requirements and minimal coolant volume. Flow boiling heat sinks can operate at much higher heat flux and more uniform temperature requirements and minimal coolant volume. Flow boiling heat sinks can also be improved by locally extracting vapor from two-phase flows; several studies [6–11] have confirmed this both numerically and experimentally. Also, the optimization of the design of the fractal-like branching network was studied by Heymann et al. [12,13]. Studies suggest that the pressure drop across microscale heat sinks can also be improved by locally extracting vapor from two-phase flow through a hydrophobic, porous membrane forming one wall of the channel [14–16]. Apreotesi et al. [14,15] provided experimental results of diabatic boiling water flowing through a fractal-like microchannel heat sink with local vapor extraction that show a decrease in overall channel pressure drop as the extraction pressure difference increases. A study by David et al. [16] with flow boiling in a microchannel heat sink used one wall fabricated from a hydrophobic porous membrane to allow venting of the vapor. Their experimental results with vapor venting show a significantly reduced pressure drop when compared to the non-venting results. Also, David et al. [17] discuss various flow regions with both adiabatic and diabatic flow with venting.

To model pressure drop, separated flow models have been used for two-phase flow in minichannels and microchannels. Most separated flow models are based on the Lockhart and Martinelli [18] relationship, such as the models presented by Mishima and Hibiki [19], Lee and Lee [20], Qu and Mudawar [21], Lee and Mudawar [22], and Hwang and Kim [23]. All of these predictive models do show good agreement with specific experimental data.
Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$Bo$</td>
<td>boiling number</td>
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<tr>
<td>$c_p$</td>
<td>specific heat</td>
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<tr>
<td>$C_{IM}$</td>
<td>phase interaction parameter</td>
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<tr>
<td>$D_h$</td>
<td>hydraulic diameter</td>
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<tr>
<td>$f_{loc}$</td>
<td>local liquid phase friction factor</td>
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<tr>
<td>$G$</td>
<td>mass flux</td>
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<td>$h$</td>
<td>heat transfer coefficient</td>
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<td>$H$</td>
<td>channel depth</td>
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<tr>
<td>$i$</td>
<td>enthalpy</td>
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<tr>
<td>$i_v$</td>
<td>heat of vaporization</td>
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<tr>
<td>$k$</td>
<td>channel branching level</td>
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<tr>
<td>$L$</td>
<td>channel branching length</td>
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<tr>
<td>$L_{tot}$</td>
<td>total flow length</td>
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<tr>
<td>$n$</td>
<td>number of branches</td>
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<tr>
<td>$M$</td>
<td>number of branching levels</td>
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<tr>
<td>$MAE_{\Delta P_{chan}}$</td>
<td>mean absolute error between model and experimental results of $\Delta P_{chan}$</td>
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<tr>
<td>$MAE_{\Delta m_{extr}}$</td>
<td>mean absolute error between model and experimental results of $\Delta m_{extr}$</td>
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<td>$m_{in}$</td>
<td>inlet mass flow rate</td>
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<tr>
<td>$m_{extr}$</td>
<td>extracted vapor mass flow rate</td>
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<tr>
<td>$N_0$</td>
<td>number of inlet branches</td>
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<td>$N_k$</td>
<td>number of kth level channels</td>
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<td>$P_{extr}$</td>
<td>extraction absolute pressure</td>
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<td>$\Delta P_{vap}$</td>
<td>vapor pressure gradient</td>
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<tr>
<td>$Q$</td>
<td>heat rate</td>
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<tr>
<td>$R_{extr}$</td>
<td>extraction flow resistant</td>
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<tr>
<td>$Re$</td>
<td>Reynolds number</td>
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<td>$T$</td>
<td>temperature</td>
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<td>$v$</td>
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<tr>
<td>$w_t$</td>
<td>terminal branch width</td>
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<tr>
<td>$\phi_l$</td>
<td>two-phase multiplier</td>
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<tr>
<td>$\delta$</td>
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<td>$\beta_w$</td>
<td>width ratio</td>
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<tr>
<td>$\gamma$</td>
<td>length ratio</td>
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<tr>
<td>$\Delta P_{chan}$</td>
<td>channel pressure drop</td>
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<tr>
<td>$\Delta P_{extr}$</td>
<td>local extraction driving pressure</td>
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<tr>
<td>$\Delta P_{extr}$</td>
<td>extraction pressure differential ($\Delta P_{extr} = P_{chan, out} - P_{extr}$)</td>
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Subscripts

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<th>Symbol</th>
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<tr>
<td>$acc$</td>
<td>acceleration</td>
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<tr>
<td>$back$</td>
<td>porous backing</td>
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<td>$fric$</td>
<td>frictional</td>
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<tr>
<td>$in$</td>
<td>inlet</td>
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<tr>
<td>$l$</td>
<td>liquid phase</td>
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<tr>
<td>$lo$</td>
<td>all-liquid</td>
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<tr>
<td>$mem$</td>
<td>porous membrane</td>
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<td>$out$</td>
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<td>$sat$</td>
<td>saturation</td>
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<td>$v$</td>
<td>vapor phase</td>
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<tr>
<td>$s$</td>
<td>surface</td>
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The present study has the added complexity of vapor extraction along the channel across a porous membrane. The process can be related to vacuum membrane distillation, which has been described in a number of studies [24–27]. Basically, distillation uses thermally induced transport of vapor through a porous hydrophobic membrane. A heated, aqueous feed solution is brought into contact with the feed side of the membrane. Vapor flow through the membrane has been successfully modeled based on Darcy’s law, using the local vapor pressure difference across a membrane of a given permeability.

In order to predict the pressure differential across the membrane, it may be necessary to predict the local wall temperature, using a local heat transfer coefficient. As discussed later, this is to determine a film temperature based vapor pressure. For two-phase boiling flow, flow boiling heat transfer can be divided into nucleate boiling and convective boiling components. The boiling heat transfer coefficient of the nucleate boiling is a function of wall heat flux only whereas convective boiling is a function of quality and mass velocity. Some studies [28,29] suggest that the nucleate boiling mechanism is dominant. Others [30–36] show that the boiling heat transfer coefficient is affected by quality and mass velocity as well as wall heat flux. Bertsch et al. [2] and Ribatski et al. [3] analyzed the experimental results for microscale two-phase flow from various investigators and conclude that the existing flow boiling heat transfer correlations poorly predicts the experimental database. For this study, the model from Lee and Mudawar [36] is used.

In this paper, a predictive one-dimensional model for flow boiling in a microscale fractal-like branching network with local vapor extraction for a range of heat flux and mass flow rate are presented and discussed. Several options of the local extraction driving pressure which drives flow across the membrane are presented. Pressure drop, temperature distribution and extracted vapor mass flow rate are presented. The results are compared with the experimental data of Apreotesi et al. [14,15] for relatively low flow rates and low heat flux conditions; experimental high flow rates and high heat flux data are not available in the literature.

2. Flow geometry

In this study, a generalized model for vapor extraction is developed and applied to a fractal-like branching microchannel heat sink. A cross-section schematic of the flow channel is shown in Fig. 1, whereas representative planform views are provided in

![Fig. 1. Schematic cross-sectional of assembled heat sink (adapted from [14]).](image-url)
Fig. 2. Flow enters from the center of the disk and flows radially through the branching channels. In the experimental investigation, (Apreotesi et al. [14,15]) a hydrophobic porous membrane with a porous aluminum backing for support serves as the porous top wall of the channels. The porous aluminum block had an embedded resistance heater to assure no vapor condensation within the block. The vapor is drawn through the hydrophobic membrane and porous aluminum by applying a vacuum to a plenum located above the aluminum. These conditions are incorporated into the model.

A single branch from the experimental test device is shown in Fig. 3 where the integer index \( k \) indicates the level of the channel with the \( k = 0 \) level originating at the inlet plenum. There are two types of fractal-like microchannel networks numerically investigated in this study: one with a fixed hydraulic diameter ratio and the other with a fixed width ratio. In all cases, the channel depth, \( H \), remain fixed. The fractal-like network used by Apreotesi et al. [14] has a fixed hydraulic diameter ratio, \( b_{Dh} \), and a fixed length ratio, \( c \), between the upstream channel level, \( k \), and the downstream channel level, \( k + 1 \), using the following scaling laws:

\[
\beta_{Dh} = \frac{D_{h,k+1}}{D_{h,k}}
\]

\[
\gamma = \frac{L_{k+1}}{L_k}
\]

In general, the number of branches into which an upstream channel may split is given by \( n \), in this case, \( n = 2 \), and \( N_0 \) is the number of initial branches emanating radially from the inlet plenum. Consequently, the number of branches at each level \( k \) becomes:

\[
N_k = N_0 n^k
\]

The total length of the channels in the network, \( L_{tot} \), is obtained from the summation:

\[
L_{tot} = \sum_{k=0}^{M} L_k
\]

where \( M \) is the total number of branching level streamwise bifurcations. In Fig. 3, \( M = 4 \) resulting in 5 levels.

The second type of the fractal-like branching network is based on a fixed width ratio. The fractal-like aspects of this geometry are the same as previously described except the width ratio is fixed instead of hydraulic diameter ratio. The width ratio, \( b_w \), is defined by:

\[
\beta_w = \frac{W_{k+1}}{W_k}
\]

where \( W \) is the channel width. This design was first proposed and recommended by Pence and Enfield [37] because a fixed hydraulic diameter ratio with a constant channel depth expects in an infinite channel width for the lower order branching levels for \( M > 4 \). Details of the geometric variables used in this study are given in Table 1.

### Table 1

| Geometry detail of two fractal-like networks, F1 and F2, used in this study. |
|-----------------|-----|-----|
| Geometry        | F1  | F2  |
| Hydraulic diameter ratio, \( b_{Dh} \) | 0.7937 | -  |
| Width ratio, \( b_w \)            | -   | 0.7071 |
| Length ratio, \( \gamma \)          | 0.7071 | 0.7071 |
| Channel depth, \( H \)             | 250 \( \mu \)m | 150 \( \mu \)m |
| Terminal branch width, \( w_t \)   | 100 \( \mu \)m | 100 \( \mu \)m |
| Total flow length, \( L_{tot} \)   | 18.0 mm | 17.5 mm |
| Disk diameter, \( D_{disk} \)      | 36.6 mm | 35.5 mm |
| Planar area, \( A_{planar} \)      | 10.52 cm\(^2\) | 9.90 cm\(^2\) |
| Number of initial branches, \( N_0 \) | 12 | 16 |
| Number of branches per level, \( n \) | 2 | 2 |
| Number of branching level, \( M \)  | 4 | 4 |

### 3. Model description

The predictive model developed here is aimed at predicting global behavior and, once validated, can be used as a design tool for heat sink applications. The model determines the relationship
between the vapor extraction rate and the pressure drop through the microchannel network for a given heat flux and inlet mass flow rate. This model is based on conservation laws written for a one-dimensional boiling microchannel flow network. Existing correlations for channel pressure drop and heat transfer coefficients are used and are discussed below. These correlations assume that the onset of boiling occurs at a thermodynamic equilibrium quality of zero, i.e., the fluid remains a single-phase liquid until the local pressure and temperature reach the saturation conditions at which the fluid is converted to a saturated two-phase fluid. For fractal-like branching flow, the hydrodynamic and thermal boundary layers are assumed to redevelop following each bifurcation while the pressure change at each bifurcation is assumed to be negligible. This was shown to be a realistic assumption by Daniels et al. [9,10]. Although more complex flow physics associated with the boiling process during extraction is not included, it is thought that the overall pressure drop and vapor extraction prediction are still reasonably evaluated. This is because the pressure drop correlations have been validated in microchannel flows in the literature (e.g., [9,10,21]) and the vapor extraction is based on a Darcy flow through the permeable membrane, which has been validated in membrane distillation applications [24], and other applications.

3.1. Model implementation

The channel pressure drop and the extracted vapor mass flow rate are the desired outputs from the one-dimensional model. The model has been developed using conservation of mass and energy as well as a pressure drop model based on conservation of momentum for discrete elements along the microchannel accounting for local vapor mass and energy extraction. The inputs are the flow geometry, porous membrane and support backing properties, the outlet pressure, the inlet mass flow rate, the heat input, the extraction pressure, and either inlet subcooling or inlet temperature. For the fractal-like branching microchannel network, required geometric inputs are the channel height, the terminal channel width, the total length of the flow path, the number of initial branches, the number of branch levels, the length ratio and either the hydraulic diameter ratio or width ratio. The porous membrane and porous backing require inputs of their specific permeability and the thickness.

A schematic of the model transport is shown in Fig. 4. The flow path is divided into non-uniform elements. Nominally, a 5 μm element length is initially specified. Because the two-phase pressure gradient is much larger than the single-phase pressure gradient, the two-phase region nodal spacings are reduced, typically to approximately 1 μm, based on local conservation constraints. Each branching level is divided into an integer number of elements. At the bifurcation node, fluid flow is assumed to be split equally into each channel with the new cross-sectional area. The geometric details of the bifurcation are not included, although the hydraulic and thermal development models are included as mentioned earlier. A grid refinement analysis was performed. The local pressure and local quality values varied by less than 0.5% and 0.25%, respectively when the grid size was reduced by a factor of one half (2.5 μm in the single phase and 0.5 μm in the two phase region).

The model is initiated by assuming the inlet pressure for a specified exit pressure and marching in the streamwise direction to calculate the local static pressure, bulk fluid temperature, wall surface temperature and fluid properties. For each element, pressure drop and extracted vapor flow rate, based on the membrane transport model, are evaluated. The governing equations for pressure drop, membrane transport and heat transfer models are discussed in later sections. Using conservation of mass and energy, the pressure drop and the heat transfer models, each element undergoes an internal iteration to satisfy local pressure and temperature values. Upon reaching the exit of the channel, if the calculated exit pressure differs from the specified value by more than 0.05%, the inlet pressure is updated and the pressure along the entire channel length is recalculated.

The internal iteration of elements in the single-phase region includes extracted vapor mass flow rate by evaporation, which is accounted for in the energy and mass flow rates of each element. Both mass flow rate and fluid properties, which are sensitive to temperature variations, are simultaneously updated in the internal iteration. Because the liquid phase properties are not a strong function of pressure, and the pressure variation in each element in this study is small, the single-phase pressure drop of each element is evaluated after the internal iteration of conservation of mass and energy. In the two-phase region, the pressure drop calculation is included in the internal iteration because the pressure and temperature in equilibrium conditions are related. Besides mass flow rate and fluid properties, the quality in the two-phase flow is updated simultaneously in the internal iteration. This is because quality varies with both pressure and temperature and is an important parameter in two-phase pressure drop model. Further details of the model implementation are given by Salakij [38].

3.2. Conservation of mass and energy

Conservation of mass and energy is used which accounts for local vapor extraction for the discretized control volume, as shown in Fig. 4:

\[ \dot{m}_i = \dot{m}_{i-1} - \dot{m}_{\text{extr},i} \]  

and

\[ \dot{m}_l_i = \dot{m}_{l_{i-1}} - \dot{m}_{\text{extr},i} \]  

The last term in Eqs. (6) and (7) represents the mass flow rate of extracted vapor and its convective energy transfer rate that leaves the control volume with the extracted vapor, respectively. The enthalpy of extracted vapor, \( h_{\text{extr},i} \), is evaluated as the enthalpy of saturated vapor based on the average bulk fluid temperature inside the control volume where the extracted mass flow rate, \( \dot{m}_{\text{extr},i} \), is determined from the membrane transport model discussed in detail in a later section. In this study, there is a membrane support backing through which heat is supplied to the channel. Consequently, the membrane which forms the channel's top surface, performs as a heated surface. By assuming a constant heat flux applied to the channel’s top surface, the heat transfer rate into the element \( i \), \( Q_i \), is determined based on the element channel’s top area fraction as:

\[ Q_i = \frac{A_i}{A_{\text{chan.top}}} \]  

where

\[ A_i = w_i A_{z_i} \]  

![Fig. 4. Schematic of discretized control volume used in predictive model.](Image 83x55 to 253x156)
and 
\[ A_{\text{chan,up}} = N_0 \sum_{i=1}^{n} (2^n A_i) \]  
(10)

It should be noted that the total top area of the channel network, given in Eq. (10), is different (less) than the disk planar area.

3.3. Pressure drop model

The pressure drop for each element along the flow path is calculated individually. The pressure drop has two components: friction, \( \Delta P_{\text{fric}} \), and acceleration, \( \Delta P_{\text{acc}} \). Therefore, the pressure drop for element \( i \) in the flow network is expressed as:

\[ -\Delta P_{\text{chan},i} = -\left( \Delta P_{\text{fric},i} + \Delta P_{\text{acc},i} \right) \]  
(11)

The frictional pressure drop, \( \Delta P_{\text{fric}} \), can be determined from the product of the two-phase multiplier, \( \phi_l^2 \), and the liquid phase pressure gradient:

\[ \frac{dp}{dz}_{\text{fric}} = \phi_l^2 \frac{dp}{dz}_{\text{fric},l} = -\phi_l^2 \left( 2f_{\text{loc,lo}} (1-x)^2 G^2 \right) / \rho_D \]  
(12)

where \( f_{\text{loc,lo}} \) is the local all-liquid Fanning friction factor. Because the local all-liquid Reynolds number never goes beyond 900 for all predicted results, the flow is taken to be laminar. For laminar flow, the local friction factor is based on the apparent friction factor model given by Shah and London [39], which provides an average value up to a specific location \( z \), such that the local value can be evaluated as:

\[ f_{\text{loc,lo}} = f_{\text{app},l} + \frac{df_{\text{app}}}{dz} \bigg|_{z} \]  
(13)

where

\[ f_{\text{app},l} = \frac{3.44}{\sqrt{v_L}} + f_{\text{Re}_D}^{v_L} \left( \frac{K(\infty)}{v_L} \right) \frac{3.44}{1 + \left( \frac{v_L}{v_L} \right)^{2/5}} \]  
(14)

and

\[ \frac{df_{\text{app}}}{dz} = \frac{1}{D_{h,\text{Re}_D}} \left[ \frac{-3.44}{2(v_L)^{7/2}} + \frac{f_{\text{Re}_D}^{v_L} C}{(v_L)^{3/2}} + \frac{K(\infty)}{4(v_L)^{5/2}} \left( \frac{1}{1 - \left( \frac{v_L}{v_L} \right)} \right) \frac{3.44}{\left( \frac{v_L}{v_L} \right)^{2/5}} \right] \]  
(15)

Here the non-dimensional length is given by:

\[ z^+ = z / D_h \]  
(16)

\( K(\infty) \) is the incremental pressure defect and \( C \) is a constant dependent on the channel aspect ratio given as tabulated values in Shah and London [39]. Further model details can be found in Salakij [38]. By integrating the frictional pressure gradient, Eq. (12), across element \( i \), the frictional pressure drop across element \( i \) is evaluated as:

\[ -\Delta P_{\text{fric},i} = \frac{1}{D_h} \int_{-1}^{1} f_{\text{loc,lo}} (1-x)^2 G^2 \phi_l^2 \rho_l dz \]  
(17)

Using a trapezoidal integration approximation, Eq. (17) becomes:

\[ -\Delta P_{\text{fric},i} = \frac{Az_i}{D_h} \left[ \left( f_{\text{loc,lo}} (1-x)^2 G^2 \phi_l^2 \rho_l \right)_{i-1} + \left( f_{\text{loc,lo}} (1-x)^2 G^2 \phi_l^2 \rho_l \right)_{i} \right] \]  
(18)

It should be noted that the mass flux of fluid in the channel, \( G \), changes along the flow direction due to changes in both cross-sectional area and vapor extraction. For single-phase flow, the two-phase multiplier and quality are equal to 1 and 0, respectively. For two-phase separated flow, Chisholm [40] and Chisholm and Laird [41] present closed form expressions for the two-phase multiplier, \( \phi_l^2 \), as a function of Lockhart–Martinelli parameter, \( X^2 \), and the phase interaction parameter, \( C_{\text{LM}} \):

\[ \phi_l^2 = 1 + \frac{C_{\text{LM}}}{X^2} + \frac{1}{X^2} \]  
(19)

where \( X^2 \) is given by Carey [42]:

\[ X^2 = \frac{(dp/dz)|_v}{(dp/dz)|_{x}} = \left( \frac{\rho_{l} \mu_{l} (1-x) \sqrt{\pi} \eta_{l}}{\rho_{v} \mu_{v} \sqrt{\pi}} \right) \frac{n}{(1-x)^{2}} \left( \frac{\eta_{l}}{\eta_{v}} \right) \]  
(20)

and \( n \) is the exponent of the Reynolds number in the Blasius equation which is equal to 1 for laminar flow. The phase interaction parameter is dependent on the mass flux as proposed by Qu and Mudawar [21]:

\[ C_{\text{LM}} = 21(1 - e^{3180G})/(0.00418G + 0.0613) \]  
(21)

The acceleration pressure drop, \( \Delta P_{\text{acc}} \), in a constant area channel can be determined from the acceleration pressure gradient [42]:

\[ -\frac{dp}{dz}_{\text{acc}} = \frac{d}{dz} \left( \frac{G^2 x^2 \rho_v}{\alpha} + \frac{C_{\text{LM}} (1-X^2)^2 \eta_{l}}{(1-\alpha)} \right) \]  
(22)

where \( \alpha \) is the void fraction. The void fraction is expressed as a function of local quality, \( x \), as proposed by Zivi [43]:

\[ \alpha = \frac{1}{1 + \left( \frac{X}{X_{\text{top}}} \right)^{2/5}} \]  
(23)

It should be noted that although this void fraction correlation was not directly developed for microchannel flow, it was developed assuming annular flow which is documented to be the dominated flow pattern in microchannel [44]. By integrating the acceleration pressure gradient across element \( i \), the two-phase acceleration pressure drop across element \( i \) is evaluated as:

\[ -\Delta P_{\text{acc},i} = \left( \frac{G^2 x^2 \rho_v}{\alpha} + \frac{(1-x)^2 \eta_{l}}{(1-\alpha)} \right)_{i} - \left( \frac{G^2 x^2 \rho_v}{\alpha} + \frac{(1-x)^2 \eta_{l}}{(1-\alpha)} \right)_{i-1} \]  
(24)

For single-phase flow, the quality, \( x \), and void fraction, \( \alpha \), are set to 0.

3.4. Membrane transport model

Transport across the membrane may occur either as evaporation or bubble extraction. Evaporation will occur in the single-phase region and both modes can coexist in the two-phase flow region. The evaporative extraction, similar to membrane distillation, occurs when the liquid phase near the membrane evaporates and is then extracted through the membrane. The bubble extraction occurs when a bubble is directly in contact with the membrane and is extracted through it.

In this study, a hydrophobic membrane, matched in terms of permeability and thickness with that used in experiment. The mass transport of vapor across the membrane is based on Darcy’s law [24] and can be expressed as:

\[ \dot{m}_{v} = \rho_{v} K_{v} \nabla \phi_{v} \]  
(25)

where \( \dot{m}_{v} \) is the vapor mass flux flowing through the porous media, \( K_{v} \) is the specific permeability, \( v_{k} \) is the vapor kinematic viscosity and \( \nabla \phi_{v} \) is the vapor pressure gradient across the porous media. Because experimental data will be used to validate the model, which includes a porous backing material to support the
local extracted vapor mass flow rate of element i is expressed as:

\[ \dot{m}_{\text{extr},i} = \left( \frac{A_{\text{extr}}}{\Delta P_{\text{extr}} \left( \frac{\delta_{\text{mem}}}{\delta}, \frac{\delta_{\text{back}}}{\delta_{\text{back}}} \right)^{-1}} \right) \frac{1}{2} \]

where \( A_{\text{extr}} \) is the area of extraction and \( \Delta P_{\text{extr}} \) represents the local value of the total differential pressure across the combined membrane and porous backing.

It should be noted that mass transport across the membrane may occur due to both evaporation and bubble extraction. The model for the extracted vapor mass flux for both evaporation and bubble extraction is a function of the driving pressure differential based on the saturation pressure of the liquid for evaporative extraction and pressure of the vapor at the membrane for bubble extraction. Although these pressures in the two-phase region may be slightly different, say as a result of surface tension effects, this difference is assumed to be negligible in this model.

Three different models were evaluated for the local extraction driving pressure, \( \Delta P_{\text{extr,loc}} \), which are shown in Table 2, where the local channel pressure is denoted by \( P_{\text{chan,loc}} \) and \( P_{\text{extr}} \) is the extraction pressure, both expressed as absolute pressures. The first model, denoted as Eq. (27) in Table 2, is based on a driving pressure differential using the local bulk pressure in the channel. This was used by Apureotesi [15] where vapor was assumed to be only extracted when vapor phase is present, i.e. thermodynamic equilibrium quality is greater than zero. Consequently this model does not account for evaporation in the single-phase liquid region. The other two models, Eqs. (28) and (29), relax this restriction and allow vapor to be extracted from the liquid phase by evaporation in both single-phase and two-phase regions. The driving pressure in the second and third models is based on the saturation pressure on the channel side of the membrane. In the second model, Eq. (28), the saturation pressure is defined using the bulk channel temperature, \( T_b \), as the saturation temperature and in the third model, Eq. (29), the saturation pressure is determined using a film temperature, \( (T_{\text{film}} + T_b)/2 \), to represent the local saturation temperature. The idea in the latter model is that the driving mechanism for vapor transport based on Darcy flow through the membrane is related to the local saturation pressure adjacent to the membrane. Consequently, the third model requires determination of the wall temperature which can be determined based on the local heat transfer coefficient.

### Table 2

Local extraction driving pressure models and extracted mass flow rate variation from experimental results [14,15].

<table>
<thead>
<tr>
<th>Pressure differential</th>
<th>( \Delta P_{\text{extr,loc}} )</th>
<th>( \Delta P_{\text{extr,loc}} )</th>
<th>( \Delta P_{\text{extr,loc}} )</th>
<th>( T_{\text{film}} = \left( T_{\text{film,loc}} + T_b \right)/2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_{\text{chan,loc}} - P_{\text{extr}}, x &gt; 0 )</td>
<td>20.3</td>
<td>( \frac{15.5}{27} )</td>
<td>13.2</td>
<td>( \frac{1}{2} )</td>
</tr>
<tr>
<td>( 0, x \leq 0 )</td>
<td>( \frac{15.5}{28} )</td>
<td>( \frac{13.2}{29} )</td>
<td>( \frac{1}{2} )</td>
<td>( \frac{1}{2} )</td>
</tr>
</tbody>
</table>

#### 3.5. Heat transfer model

The local heat transfer coefficient in the channel is only necessary to determine the local membrane wall temperature, which is used in turn to determine the film temperature for use in the membrane transport model, Eq. (29). It should be noted that in this study the membrane is also a heated wall for the channel flow. In the heat transfer model, thermally developing and hydrodynamically developing flow are assumed after each bifurcation. The single-phase Nusselt number in the simultaneously developing flow region of laminar flow is determined by linear interpolation of data provided by Shah and London [39]. There are a few widely disparate heat transfer coefficient models and correlations for microchannel flow boiling, (e.g. [28–36]). However, none of these have been validated for fractal-like flow geometries. The two-phase heat transfer coefficient correlation proposed by Lee and Mudawar [36] for microchannel flow boiling is used here and is given as Eqs. (30)–(32) in Table 3.

#### Table 3

Lee and Mudawar [36] boiling heat transfer correlation

<table>
<thead>
<tr>
<th>Correlation</th>
<th>Eq.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–0.05</td>
<td>( h_{2p} = 3.856X^{0.267}h_{1p,1} )</td>
</tr>
<tr>
<td>0.05–0.55</td>
<td>( h_{2p} = 436.48Bo^{0.522}We^{0.351}X^{0.665}h_{1p,1} )</td>
</tr>
<tr>
<td>0.55–1.0</td>
<td>( h_{2p} = \max{108.6X^{1.665}h_{1p,F}, h_{1p,F}} )</td>
</tr>
</tbody>
</table>

#### 4. Model validation

Pressure drop calculations were validated using a fractal-like branching network used to obtain adiabatic experimental data with no vapor extraction by Daniels et al. [10]. The fractal-like flow network is designated as F2 in Table 1 and is represented in Fig. 2(b). The accuracy of the predictions was assessed using the mean absolute error, defined as:

\[ \text{MAE}_{\text{chan}} = \frac{1}{N} \sum_{i=1}^{N} \left| \frac{\Delta P_{\text{chan,exp}} - \Delta P_{\text{chan,pred}}}{\Delta P_{\text{chan,exp}}} \right| \]

Fig. 5 shows comparison between the model and experimental results. The predicted channel pressure drops yield very good agreement with the experimental data, a mean absolute error of 5.5%.

Diatomic vapor extraction predictions are compared with the experimental data of Apureotesi et al. [14,15] based on the fractal-
like flow network F1 in Table 1 and represented in Fig. 2(a). Vapor extraction mass flow rates based on all three extraction driving pressure models, given in Table 2, are compared with experimental values in Fig. 6. The accuracy of the predictions for all models based on the mean absolute error is shown in Table 2. All models are within approximately 10–20% of measured values with predictions using the saturation pressure based on film temperature yielding the best results. These results support the hypothesis that the saturated pressure based on the local average film temperature better represents the local saturated pressure adjacent to the membrane than the others. This may be a consequence of sufficiently large temperature gradients near the wall which influence the local vapor pressure, modeled as the saturation pressure at the film temperature. This results in an increase in mass flux compared to basing the transport on the bulk channel pressure.

Comparisons of the predicted and experimental results of Apreotesi et al. [14,15] for the vapor mass flow rate versus extraction pressure differential are shown in Fig. 7 for an inlet flow rate of 8 g/min and heat input of 18 W for fractal geometry F1. Results indicate that the predictions from the two models using the saturation pressure rather than bulk pressure more accurately reflect the trend of the experimental data. Because the saturation pressure based on the film temperature model gives the least error, 13.2%, this model was used to generate all further results presented.

5. Results and discussions

Results of model predictions are presented as both local distributions of quality, pressure and bulk temperature, as well as global results of pressure drop, exit quality and vapor extraction rates. Because the pressure and temperature vary along the channel, a global extraction pressure differential is used to characterize the results, which is defined as the difference between the extraction absolute pressure and the channel outlet pressure which represents the lowest channel pressure:

\[ \Delta P_{\text{extr}} = P_{\text{chan,out}} - P_{\text{extr}} \]  

Results are presented for the fractal-like geometry designated as F2 (given in Table 1). Water was used as the working fluid with an inlet subcooling of 2.5 K to ensure significant vapor formation. The outlet was set to atmospheric pressure, i.e. 101 kPa-a. The range of numerical model conditions is divided into two groups: (i) low inlet flow rate-low heat flux and (ii) high inlet flow rate-high heat flux. The low heat flux cases use three flow rates ranging between 8–12 g/min (or inlet mass flux of 139–208 kg/m² s), three heat inputs ranging from 18 to 30 W (or heat flux of 1.77–2.95 W/cm² based on planar heated surface area) and five extraction differential pressures ranging between 0 and 55 kPa and no extraction. The high heat flux cases use four flow rates ranging between 30 and 60 g/min (or inlet mass flux of 521–1042 kg/m² s), four heat inputs ranging from 250 to 1000 W (or heat flux of 24.56–98.24 W/cm² based on planar heated surface area) and four extraction differential pressures ranging between 0 and 61 kPa and no extraction. It should be noted that zero extraction differential pressure is not the same as no extraction because the local pressure decreases along the channel and upstream there is sufficient pressure differential to drive vapor through the membrane.

5.1. Local conditions

Five cases are presented in this section to provide representative local distributions of pressure, temperature and quality along the channel. To represent the low flow rate, low heat flux case, the following conditions are used: inlet flow rate of 10 g/min, heat input of 18 W and extraction pressure differentials of 14 and 41 kPa.

Fig. 6. Comparison of experimental [14,15] and predicted extracted vapor flow rates; with extraction pressure differential based on (a) local channel pressure (b) saturation pressure at local bulk temperature, and (c) saturation pressure at local film temperature.

Fig. 7. Extracted vapor mass flow rate as a function of extraction pressure differential. Comparison of experimental data [14,15] and three different vapor pressure models for a flow rate of 8 g/min (or inlet mass flux of 86 kg/m² s) and heat input of 18 W (or heat flux of 1.82 W/cm² based on planar heated area); the different symbols identify the channel pressure used to determine the pressure differential across the membrane.
and no extraction. For the high flow rate, high heat flux case, the conditions are: inlet flow rate of 50 g/min, heat input of 750 W and extraction pressure differential of 41 kPa and no extraction. The predicted local quality and bulk fluid temperatures are plotted as a function of streamwise location along the microchannel network in Figs. 8 and 9, respectively. The degree of local subcooling is represented by negative qualities in Fig. 8(a) where quality is defined by:

$$x = \frac{i - l_i}{l_i - l_v}$$ (35)

In Fig. 8 when the quality is above zero, phase change is implied. For the low flow rate-low heat flux case and the highest extraction pressure differential of 41 kPa, the flow remains single phase. In both the high–high and low–low flow rate–heat flux cases, local vapor extraction delays the streamwise location at which transition to two-phase flow occurs. Evident from Fig. 9 is that vapor extraction significantly reduces the local bulk temperature. This implies that the local wall temperature can be reduced by vapor extraction because of the significant energy extraction with the vapor. The saturated temperature for the given conditions coincides with the bulk temperature for the no extraction case once two-phase flow begins, indicated by the arrow in the figure. The bulk fluid temperature distribution for the 10 g/min flow rate, 18 W heat input and 41 kPa extraction pressure differential case, shown in Fig. 9(a), indicates that the bulk fluid temperature remains well below the local saturation temperature as a result of evaporative extraction, which is also shown as negative quality in Fig. 8(a). Because the overall bulk fluid temperature with vapor extraction of 41 kPa extraction pressure differential is lower than the inlet temperature, there is potential of using evaporative extraction in a single-phase heat sink to

Fig. 8. Local thermodynamic equilibrium quality with and without local vapor extraction; (a) inlet flow rate of 10 g/min, heat input of 18 W, and extraction pressure differentials of 14 and 41 kPa, (b) inlet flow rate of 50 g/min, heat input of 750 W, and extraction pressure differential of 41 kPa.

Fig. 9. Local bulk fluid temperature with and without local vapor extraction; (a) inlet flow rate of 10 g/min, heat input of 18 W, and extraction pressure differentials of 14 and 41 kPa, (b) inlet flow rate of 50 g/min, heat input of 750 W, and extraction pressure differential of 41 kPa; arrows indicate location of initial phase change, i.e. $x = 0$.

Fig. 10. Local pressure with and without local vapor extraction; (a) inlet flow rate of 10 g/min, heat input of 18 W, and extraction pressure differentials of 14 and 41 kPa, (b) inlet flow rate of 50 g/min, heat input of 750 W, and extraction pressure differential of 41 kPa.
improve the heat removal by evaporative cooling, and thereby improve overall performance.

The variation in channel pressure along the flow direction is shown in Fig. 10 for the same conditions as Figs. 8 and 9. Fig. 9(a) shows that the thermodynamic quality significantly decreases as vapor is extracted from the low flow rate-low heat flux case. The pressure distributions for these cases indicate the expected decrease in pressure drop. However, because total pressure drops of these cases are very low, the pressures show little change. For the higher flow rate-higher heat flux cases where much larger pressure drops occur, the two-phase pressure drop is significantly reduced when vapor is extracted. This large decrease in overall pressure drop is because the two-phase pressure drop is a strong function of quality, and these cases generate significant vapor, shown as high quality in Fig. 8(b). This significant drop in pressure occurs despite the fact that all of the vapor is not extracted from the channel.

The local extraction driving pressure that drives vapor through the membrane is shown in Fig. 11. The extraction driving pressure depends on the extraction driving pressure model that is used. As stated previously, the model based on the difference between the saturation pressure at the film temperature and the extraction pressure, Eq. (2), is used because it is shown to give the best agreement with experimental data.

The extraction driving pressure distributions along the channels show a significant number of step changes, which are not necessarily realistic and are an artifact of both the pressure drop and surface temperature models. The transition from single-phase to two-phase flow produces a step change in heat transfer coefficient and consequently wall temperature. In addition, the Lee and Muda-war [36] heat transfer model has three regions resulting in step changes based on the local quality, shown in Table 3. Lastly, imposing flow redevelopment at each bifurcation also results in a surface temperature step change at the beginning of each bifurcation. Although the step changes noted in these figures of the pressure differential profile are not expected to be realistic, the overall global results are shown to well predict total mass extraction rates, shown in Figs. 6 and 7, and pressure drop data, shown in Fig. 5. It may be concluded that these local profile singularities are not significant in predicting overall global results.

Fig. 11 also indicates the local pressure difference between the channel pressure and the extraction pressure. Results show that, in the single-phase flow region, local values of this pressure difference can be either greater or less than the local extraction driving pressure using Eq. (2). The relative value depends on the wall heat flux, heat transfer coefficient and degree of local subcooling which are used to calculate the film temperature, and in turn used in the extraction driving pressure model. Based on this result, it can be concluded that the average extraction driving pressure does not proportionally increase as the extraction pressure increases. Also, the average value of the difference between channel pressure and the extraction pressure may not well represent the average of the local extraction driving pressure. It should be noted that, unlike for the single-phase flow region, local extraction driving pressure in the two-phase flow region is always greater than the local value of pressure difference between extraction pressure and channel pressure because, in equilibrium saturated conditions, the channel pressure is equal to the saturated pressure at the bulk fluid temperature and the membrane film temperature is always greater than the bulk temperature. It is therefore suggested that a heated membrane wall improves vapor extraction efficiency especially in the two-phase region because it increases the effective extraction driving pressure due to higher film temperature.

5.2. Global results

Global mass and energy balances were carried out based on inlet and exit conditions, including the flow and energy through the membrane. The global results consist of the total extracted mass flow rate, exit quality and channel pressure drop. The total extracted vapor mass flow rate and the exit quality are plotted as a function of the extraction pressure differential in Figs. 12 and 13, respectively. In Fig. 13 the horizontal arrows indicate the exit quality for no extraction for the various heating rates. Fig. 12 illustrates the increase in extracted vapor mass flow rate with increasing extraction pressure differential. It should be noted that the zero extraction pressure differential condition still results in some mass extraction through the membrane and an exit quality slightly less than the no extraction case. This is due to vapor extraction that occurs across the membrane because zero differentials are based on the exit conditions and as such vapor can be transported due to a pressure differential near the inlet portions of the channel. At higher pressure differentials, the extracted mass flow rate asymptotically reaches a value dependent on the heat input rate. For the low flow rate-low heat flux case, Fig. 12(a), all heating rates result in nearly the same mass extraction at low extraction pressure differentials. As \( \Delta P_{\text{ext}} \) increases, the lower heating cases show a decreasing extraction rate, but eventually all cases show a reduction in the rate of increase of mass extraction versus \( \Delta P_{\text{ext}} \), that is the slope decreases. The reason for this can be explained by examining Fig. 13(a). As expected, the exit quality decreases as the extraction pressure differential increases, shown in Fig. 13(a). The exit quality can be decreased to zero or a negative value if sufficient energy is extracted with the vapor. The extraction pressure differential required to obtain zero or negative exit quality depends on the heat input rate. As the heating rates increase, a higher
extraction pressure differential is required to remove sufficient 

region, which is where there is a distinct difference in the mass 

under these circumstances extraction is purely evapora-

As the heating rate increases the liquid phase en- 


event is required per mass for vaporization. Results indicate 
an asymptotic limit to the mass extraction rate that is higher for 

For the high flow rate-high heat flux cases, shown in 

higher channel pressures and higher pressure differentials for 

Also, at these higher heating rates, the local membrane wall 

This results in higher film temperature values. Therefore, 

The predicted overall pressure drop is presented as a func-

The two-phase pressure drop along the channel initially 

The pressure drop is reduced by increasing the extraction 

The network pressure drop versus the extraction pressure dif-

Fig. 12. The extracted vapor mass flow rate versus the extraction pressure differential for a range of heat input values for an inlet mass flow of (a) 10 g/min and (b) 50 g/min.

Fig. 13. The exit quality versus the extraction pressure differential for a range of heat input values for an inlet mass flow of (a) 10 g/min and (b) 50 g/min.

Comparing Figs. 12(a) and 13(a), the no boiling condition (that is \( x_{\text{out}} \) less than zero) coincides with the high extraction pressure differential is required to remove sufficient vapor, and energy, to maintain an exit quality of zero.

Comparing Figs. 12(a) and 13(a), the no boiling condition (that is \( x_{\text{out}} \) less than zero) coincides with the high extraction pressure differential region, which is where there is a distinct difference in the mass extraction for the different heating rates. Under these circumstances extraction is purely evaporative such that higher heat inputs evaporate more vapor at a given extraction pressure. As the heating rate increases the liquid phase enthalpy increases and less energy is required per mass for vaporization. Results indicate an asymptotic limit to the mass extraction rate that is higher for higher heating rates.

For the high flow rate-high heat flux cases, shown in Figs. 12(b) and 13(b), the relative increase of mass extraction and decrease in exit quality with increasing \( \Delta P_{\text{extr}} \) is noticeably smaller than for the lower flow rate cases. Note that for these flow rates and heating rate values the flow is always two-phase prior to the exit of the channel. Also the increase of extraction rate with increasing heating rate is significant. Higher heat flux results in higher channel pressures and higher pressure differentials for vapor extraction. Also, at these higher heating rates, the local membrane wall temperatures are significantly higher. This results in higher film temperature values. Therefore, the saturation pressure near the wall increases which increases the net extraction driving pressure for the same extraction pressure. Between the low and the high flow rate and heating rate extremes shown, clearly different trends emerge. The low flow rate-low heat flux cases allow for significant control over the local quality and thus the flow characteristics and pressure drop, as is shown next. At the higher flow rates and higher heating rates, the variations of both mass extraction and exit quality is much smaller, at least over the range of extraction pressure differential studied.

The predicted overall pressure drop is presented as a function of the extraction pressure differential in Fig. 14 for the low and the high flow rate-heat flux conditions. The two-phase pressure drop along the channel initially decreases nearly linearly as the extraction pressure differential increases. The pressure drop is reduced by increasing the extraction pressure differential to the point where single-phase pressure drop occurs, seen in Fig. 14(a) when...
the extraction pressure differential is greater than 40 kPa. Once this occurs, the pressure drop in this region is nearly independent of heating value. In the single-phase flow regime, the pressure drop slightly increases rather than decrease when the extraction differential pressure increases. This is because as the energy is extracted from the liquid flow, the fluid’s temperature decreases, and the viscosity increases. Consequently, excessive extraction can be somewhat detrimental to channel pressure drop. For the high flow rate-high heat flux cases shown in Fig. 14(b), for the range of extraction pressures study the flow remains two-phase. There is a modest monotonic decrease in channel pressure drop with extraction pressure differential, with the largest decrease for the highest heat input. However, the relative pressure drops are all comparable (less than 30% change). These results indicate that vapor extractions impact on pressure drop is most effective at relatively low flow rate conditions on a per channel bases. This is because of the higher fraction of vapor extracted, shown in Fig. 13. Therefore, using a large channel array would be beneficial for the same total flow rate.

Because the quality is an important parameter in determining the two-phase pressure drop, it is useful to understand the relationship between pressure drop and exit quality. Apreotesi et al. [14] introduced the ideal exit quality that would occur without vapor extraction, denoted as $x_{\text{out}}^*$. This quality is obtained from a global energy balance, while neglecting the change of the channel pressure in determining exit conditions. This quality is a function of inlet flow rate, heat input, and degree of subcooling and is expressed as:

$$x_{\text{out}}^* = \frac{\dot{Q}}{\dot{m}_0 C_p} (T_{\text{sat},\text{in}} - T_{\text{in}})$$

where all symbols are defined in the Nomenclature.

The predicted network pressure drop versus $x_{\text{out}}^*$ is presented in Fig. 15 for the low and the high flow rate-heat flux conditions. The pressure drop increases as the ideal exit quality without vapor extraction, $x_{\text{out}}^*$, increases. Results for the low flow rate-low heat flux cases, in Fig. 15(a), show the channel pressure drop increases with $x_{\text{out}}^*$ because more vapor is formed within the channel. However, at higher extraction pressure differential, this trend is reversed because vapor content is totally eliminated. For high heat flux-high inlet flow rate cases, in Fig. 15(b), the rate of increase of the pressure drop versus $x_{\text{out}}^*$ for flow without vapor extraction is larger than the cases with vapor extraction. This indicates that the pressure drop reduction due to vapor extraction is more effective when the ideal vapor quality without vapor extraction is high. Because the two-phase pressure drop varies with vapor quality, at high quality the pressure inside the channel is also high, resulting in a large local extraction driving pressure and consequently larger vapor extraction. By increasing the extraction differential pressure, the extracted vapor flow rate increases and the exit quality decreases. However, for high vapor content cases, which occur for the high heat flux cases, decreasing the absolute extraction pressure might not be sufficient to obtain zero or negative exit quality.

To better illustrate the impact on channel pressure drop, the pressure drop reduction ratio is used to represent the vapor extraction effectiveness. This pressure drop reduction ratio is defined as $(\Delta P_{\text{chan},0} - \Delta P_{\text{chan}})/\Delta P_{\text{chan},0}$ where $\Delta P_{\text{chan},0}$ is the pressure drop for no extraction. Results are shown versus $x_{\text{out}}^*$ in Fig. 16. As expected, the pressure drop reduction ratio increases as the extraction pressure differential increases. For low flow rate-low heat flux cases, the vapor extraction effectiveness decreases as $x_{\text{out}}^*$ increases except for the cases where the exit quality is negative indicative of single-phase flow (flow rate of 10 g/min and extraction pressure differential of 41 kPa and greater). The rather large percentage changes of pressure drop are due to the high sensitivity of the two-phase acceleration pressure drop to void fraction.
The vapor extraction process is somewhat less effective in term of pressure drop reduction for the high flow rate-high heat flux cases. However, these cases still show improvements. This reduction of effectiveness is because vapor void fraction in two-phase flow with a high quality is not reduced as much because void fraction becomes less sensitive to quality when the quality is high. The general trend is that the pressure drop reduction ratio increases as $\kappa_{\text{out}}$ increases for the high flow rate-high heat flux cases where $\kappa_{\text{out}}$ is relatively large. This is the result of quantitatively large channel pressures when the quality is high which leads to large extraction driving pressures with correspondingly high extracted vapor mass flow rates. Although void fraction does not change as much when the quality is large, the reduction in vapor content inside the channel by extracted vapor due to large driving pressures may be more significant in term of reducing the pressure drop.

The predicted pressure drop and extracted vapor mass flow rate is largely affected by the membrane permeability for a given extraction pressure, as is shown in Fig. 17. This plot shows channel pressure drop and extracted mass flow rate versus the extraction flow resistance, $R_{\text{extr}}$, which in this study is defined as:

$$R_{\text{extr}} = \left( \frac{\delta_{\text{mem}}}{\kappa_{\text{mem}}} \right) + \left( \frac{\delta_{\text{back}}}{\kappa_{\text{back}}} \right)$$

which accounts for both the membrane and porous backing resistances. This result is for a given flow rate, heat flux and extraction pressure differential. However, all conditions follow this same trend. Here the resistance is normalized by the resistance value used in this study denoted as $R_{\text{extr,0}}$. It should be noted that increasing the permeability is equivalent to reducing $R_{\text{extr}}$ and thereby increasing $R_{\text{extr}}/R_{\text{extr,0}}$. As shown, the amount of vapor extraction increases with decreasing $R_{\text{extr}}$, resulting in reducing exit quality and reduced channel pressure drop. In this example, sufficient extraction occurs near $R_{\text{extr}}/R_{\text{extr,0}} = 10$ to cause the two-phase flow to become single-phase flow for this high flow rate-high heat flux case. Beyond the tenfold increase in permeability, there is no further increase in vapor extraction or a reduction in channel pressure drop.

6. Conclusions

The development of a predictive one dimensional model of flow boiling in a microchannel flow network with local vapor extraction has been presented and discussed with results of the effect of mass extraction on the local and global pressure drop, bulk temperature, and quality. The predictive model is based on conservation of mass and energy, coupled with pressure drop and heat transfer correlations used for microchannel flow with boiling. The extraction rate was modeled with Darcy’s law for flow through the porous membrane. Based on the vapor extraction rate validation, the channel pressure adjacent to the membrane that drives the vapor through the membrane is best represented by the saturated pressure based on the local average film temperature rather than the bulk channel pressure. The predictive model, as applied to a fractal-like microchannel flow network, confirms the premise that the vapor extraction helps to reduce two-phase pressure drop. This is shown to be a consequence of decreased local quality resulting in reduced two-phase pressure drop. The percent decrease in pressure drop is much higher for the low channel flow rate cases, but even for large heat transfer conditions where the overall pressure drops are much larger due to larger flow rates, the decrease in pressure drop can be over 25%. The extracted vapor mass flow rate is shown to be dependent on the extraction pressure, the inlet mass flow rate and the applied heating rate. Vapor extraction is shown to reduce the bulk fluid temperature within the channel. This additional means of energy transfer has the potential to reduce the overall operating temperature of the heat sink.

The ultimate goal of the one dimensional model is its use to optimize operating conditions to minimize channel pressure drop and increase overall heat transfer rates or heat flux conditions. There are several recommendations suggested to improve the predictive model. New heat transfer and pressure drop models need to be developed to eliminate step changes in local pressure and wall temperature. However, it is shown that the current models match well with experimental data globally, but a wider range of operating conditions are needed to further verify the model. Once detailed local data are available, mechanistic models for pressure drop with vapor extraction may be possible so that optimal membrane characteristics could be identified.

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References


