Thermophysical phenomena of working fluids of thermocapillary convection in evaporating thin liquid films

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A B S T R A C T
The progressive evaporation in a thin liquid film is sustained by the circulation of its working fluid. Due to the surface tension gradient which is temperature dependent, thermocapillary flow is induced and the evaporation is impeded. We employ the long-wave theory to derive a two-dimensional mathematical model based on the first principles for polar and nonpolar liquids. The thermocapillary disparities among different types of working fluid are explicitly observed and the changes entailed in the heat transfer characteristics are scrutinized. By comparing the models with and without thermocapillary effect for different types of working fluid, it can be observed that the evaporative mass and heat rates are overrated when thermocapillary effect is neglected and the overestimates increase with increasing excess temperature. For different types of working fluid under the same operating conditions, the variations of thermo-physical properties induce different temperature gradient magnitudes in the liquid phase, incurring a different degree of thermocapillary effect on the heat transfer characteristics. The significance of surface tension gradient in thermal performance of working fluid is justified. This study evinces that by neglecting the thermocapillary effect, acute errors can be incurred even at a sufficiently small excess temperature for certain types of fluid in the heat transfer analysis of an evaporating thin liquid film.

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1. Introduction

Thin film evaporation associated with phase-change heat transfer in micro-scale cooling devices manifests itself in superior electronic cooling applications due to the high heat transfer coefficients [1–3]. An evaporating thin film forms an extended meniscus which can be typically divided into three regions, namely the equilibrium non-evaporating (adsorbed) film region, the evaporating film region, and the intrinsic meniscus region [4,5], as depicted in Fig. 1. The high heat transfer rate takes place in the evaporating film region which dominates the heat transfer process [6–8]. The evaporation of a liquid thin film is governed by the transport processes of the working fluid. In addition to the latent heat, other thermo-physical properties are also important in characterizing the evaporation process. Judging from this, the selection of appropriate working fluid for a designated range of operating temperature is an important issue in delineating the thermal performance of a two-phase cooling device [9–13]. By considering different types of common working fluid, it has been pointed out that the heat transport capacity of such device is dominated by the circulation rate, which is the ratio of the surface tension and dynamic viscosity of the working fluid [10,13].

The Marangoni effect which is attributed to the presence of surface tension gradient draws the liquid to flow away from low-surface-tension regions [14]. The surface tension gradient can be provoked either by a concentration gradient or a temperature gradient. The thin film evaporation in the capillary structures gives rise to a temperature gradient and hence a surface tension gradient along the interface, incurring a form of Marangoni convection which is regarded as thermocapillary flow [15]. The continuous evaporation of liquid at the evaporating film region is replenished by the liquid circulation from the intrinsic meniscus region. However, the net thermocapillary effect creates an opposing force which drives the flow from the evaporating film region to the intrinsic meniscus region, thus retarding the circulation strength of an evaporating thin liquid film, as shown in Fig. 1. In most of the steady evaporation of thin liquid film related problems [16–21], the impact of thermocapillary effect on its thermal behavior has not been explicitly addressed. Most of the pure liquids, both organic and inorganic, have negative surface tension gradient with respect to temperature and the thermocapillary flow occurs from high temperature regions to low temperature regions. This type of Marangoni flow is inherently associated with the Marangoni number which is defined as the ratio of surface tension to viscous force. These forces are pertinent to the thermo-physical properties of the fluid. Recently, thermocapillary flow in thin film induced by Joule heating which is referred as thermocapillary enabled purification has been employed as a promising purification technique to remove metallic carbon nanotubes from quartz substrates [22,23]. However, by employing
the evaporative mass flux model involving the extended Clapeyron equation, most prior studies on evaporating thin film excluded the thermocapillary stresses [4–8,24,25]. Particularly, investigation on the effects of working fluid on thermocapillary convection in evaporating thin liquid films has been perennially lacking. The only relevant study focused on the polarity effects of different working fluids on the heat transfer characteristics of evaporating thin films [26]. The polarity of a liquid is intimately related to the disjoining pressure which induces strong effects on the adsorbed film thickness and hence the liquid film thickness profiles.

By employing the long-wave evolution model and using heptane (a nonpolar liquid) as the working fluid, Lim and Hung [27] pointed out that when the thermocapillary effect is neglected, thinner film thickness is induced due to the absence of the opposing force and the evaporation rate is overrated. In addition, the thermocapillary effect becomes more significant at higher evaporation rate and adsorbed film thickness which is intrinsically associated with the disjoining pressure as well as the polarity of the working fluid. Therefore, it is instructive to investigate the interrelationship between the thermocapillary effect and the type of working fluid with different thermo-physical properties and polarities. In this work, we employ the long-wave evolution theory [28,29] to derive a mathematical model based on the first principles that govern the fluid flow and heat transfer characteristics of evaporating thin films for polar and nonpolar liquids. We delineate the essential attributes of the underlying thermo-physical phenomena of working fluid in affecting the thermal behavior of thermocapillary convection in evaporating thin liquid films. The thermocapillary characteristics and the thermal performance of different types of working fluid are elucidated by analyzing the deviations between the models with and without thermocapillary effect. Imperative information is obtained from the exposition of the changes entailed in the thermal characteristics due to the incorporation of the thermocapillary effect for different types of working fluid.

2. Mathematical formulation

2.1. One-sided model formulation

As depicted in Fig. 1, a thin liquid film of Newtonian fluid with constant fluid properties is bounded above by its saturated vapor at temperature $T_s$ and below by a locally heated wall with temperature $T_w$. It is assumed that no evaporation and liquid flow prevails in the non-evaporating region, in which case the film thickness approaches the adsorbed film thickness, $\delta_0$. The steady-state liquid–vapor interface is given by $y = \delta_0(x)$, where $y$ is the vertical coordinate and $\delta$ is the liquid film thickness which is a function of the longitudinal coordinate, $x$. By neglecting the gravity effect, the momentum equation of the thin liquid layer is

$$\rho \mathbf{v} \cdot \nabla \mathbf{v} = -\nabla p + \mu \nabla^2 \mathbf{v}$$

(1)

where $\rho$ is the liquid density, $\mu$ is the dynamic viscosity, $p$ is the liquid pressure and $\mathbf{v}$ is the liquid velocity vector comprising components $u$ and $v$ in the $x$- and $y$-directions, respectively. The principles of mass conservation and energy conservation are, respectively, given by

$$\nabla \cdot \mathbf{v} = 0$$

(2)

and

$$\mathbf{v} \cdot \nabla T = \kappa \nabla^2 T$$

(3)

where $T$ is the temperature and $\kappa$ is the thermal diffusivity. The outward unit normal vector is expressed as $\mathbf{n} = (1 + \delta_0^2)^{-1/2} \mathbf{t} - \delta_0 \mathbf{e}_x$ while the tangential vector is expressed as $\mathbf{t} = (1 + \delta_0^2)^{-1/2}(1, \delta_0)$. In the outward normal direction, the jump mass balance and the jump energy balance at the liquid–vapor interface are, respectively, given by

$$J = \rho \mathbf{v} \cdot \mathbf{n}$$

(4)

and

$$J_L = -k \nabla T \cdot \mathbf{n}$$

(5)

where $J$ is the mass flux, $L$ is the latent heat of vaporization and $k$ is the liquid thermal conductivity. Based on the kinetic theory, the mass flux is expressed as [30]

$$J = \frac{\alpha \rho^{(v)} \delta}{T_s^{1/2}} \left( \frac{M_w}{2 \pi R} \right)^{1/2} \left( T - T_s \right)$$

(6)

where $\alpha$ is the accommodation coefficient, $\rho^{(v)}$ is the vapor density, $M_w$ is the molecular weight of the liquid, $R$ is the universal gas constant, $\kappa$ is the thermal conductivity, $\gamma$ is the surface tension,

Greek symbols

$\delta_0$ adsorbed film thickness (m)

$\delta$ liquid film thickness (m)

$\gamma$ surface tension gradient (N/m K)

$\kappa$ thermal diffusivity (m$^2$/s)

$\lambda$ wave number

$\mu$ dynamic viscosity (N s/m$^2$)

$\nu$ kinematic viscosity (m$^2$/s)

$\rho$ liquid density (kg/m$^3$)

$\rho^{(v)}$ vapor density (kg/m$^3$)

$\sigma$ surface tension (N/m)

$\sigma_0$ surface tension at saturation reference temperature (N/m)

$\tau$ rate of deformation tensor in liquid (s$^{-1}$)

$\Pi$ disjoining pressure (Pa)
uid are much larger than those of the vapor, we simplify Eq.(7) as
\[ \gamma = \sigma(1 + \delta_s^2)^{-1/2} \]
where \( \delta_s \) is the surface tension at the reference temperature \( T_s \) and \( \gamma = -d\sigma/dT \) is the surface tension gradient. The disjoining pressure for nonpolar liquids consists of a molecular component which is expressed in terms of the film thickness as [4]
\[ \Pi = A' \delta^{-1} \]
where \( A' = A/6\sigma t \) and \( A' \) is the Hamaker constant. For polar liquids, the disjoining pressure involving molecular and structural components which are employed in a stable evaporating thin liquid, is given by [24]
\[ \Pi = A' \delta^{-1} + K'e^{-\delta_s/\ell} \]
where \( K' \) and \( \ell \) are the empirical parameters. For a combination of water and mica substrate, the values of \( K' \) and \( \ell \) are \( 3 \times 10^3 \) N/cm\(^2\) and 0.8 nm, respectively [31]. By considering surface tension gradient into the evaporating thin liquid, the shear stress balance can be expressed as
\[ J\left(v-v^{(n)}\right) \cdot n = -\nabla \tau \cdot n = -\nabla \sigma \cdot n \]
where \( \tau \) is the stress tensor in vapor, \( \sigma \) the density, \( \Pi \) is the disjoining pressure involving molecular and structural components, \( J \) the capillary pressure on the right-hand side of Eq.(8) is given by applying the no-slip condition at the interface, i.e. \( (v-v^{(n)}) \cdot n = 0 \), the shear stress balance can be simplified as
\[ \Pi \cdot n \cdot t = \nabla \sigma \cdot n \]
The term on the left-hand side of Eq. (15) is expressed as
\[ \nabla \sigma \cdot n = -\gamma(T_s + T_v \delta_s) \left(1 + \delta_s^2\right)^{-1/2} \]
and the term on the right-hand side is given by
\[ -\gamma(T_s + T_v \delta_s) \left(1 + \delta_s^2\right)^{-1/2} \]

Following Burelbach et al. [29], the dynamics of vapor phase is decoupled from the dynamics of liquid phase and the steady-state one-sided model of evaporation is formulated.

The governing equations and the boundary conditions can be rendered non-dimensional by scaling the pertinent variables. Length is scaled by the adsorbed film thickness \( \delta_0 \). Velocity and pressure are, respectively, scaled by the viscous scales: \( v/\delta_0 \) and \( \mu v^2/\delta_0^2 \). Temperature and mass flux are scaled, respectively, by \( (T - T_s)/\Delta T \) and \( k\Delta T/\delta_0 L \). [29], where the excess temperature, \( \Delta T = T_w - T_s \) is the temperature difference between the saturated temperature of vapor, \( T_w \) and the heated wall temperature, \( T_s \). Following this, we obtain the non-dimensional governing equations as
\[ \hat{u}_x + \hat{v}_y = -\hat{p}_x + \hat{u}_{xx} + \hat{u}_{yy} \]
\[ \hat{u}_x + \hat{v}_y = -\hat{p}_y + \hat{v}_{xx} + \hat{v}_{yy} \]
\[ \hat{u}_x + \hat{v}_y = 0 \]
\[ P(\hat{u}_{xx} + \hat{v}_{yy}) = \hat{T}_{xx} + \hat{T}_{yy} \]
where \( P \) is the Prandtl number defined as \( P = \nu/\kappa_c \) with \( \nu \) the kinematic viscosity of the liquid. For the boundary conditions at the liquid–vapor interface, the non-dimensional jump mass balance is expressed as
\[ EJ = \left(-\hat{u}_x + \hat{v}\right) \left(1 + \delta_s^2\right)^{-1/2} \]
where $E = k\Delta T/\rho x L$ is the evaporation number. The non-dimensional energy balance is

$$J = \left(\bar{T}_x \hat{\delta}_x - \bar{T}_y \right) \left(1 + \hat{\delta}_y^2\right)^{-1/2}$$  \hspace{1cm} (23)

The normal stress balance equation is non-dimensionalized as

$$-\hat{p}^{(v)} + \hat{p} - \Sigma \left[\hat{u}_x \hat{\delta}_x + \left(\hat{u}_y + \hat{v}_x\right) \hat{\delta}_y\right] = 0$$  \hspace{1cm} (24)

where $B = 0$ for nonpolar liquids. The non-dimensional coefficient of the structural components of disjoining pressure for polar liquids is given by $B = k' \bar{e}_{0} / \rho x^2$ while the non-dimensional Hamaker constant is given by $A = A' / (6 \bar{e}_0 x^2)$. The non-dimensional surface tension is given by $S = \sigma_0 \bar{e}_0 / \rho x^2$ and $C = \gamma \Delta T/\bar{v}_0$ is the capillary number.

The non-dimensional shear stress balance equation is given by

$$(\hat{u}_y + \hat{v}_x) \left(1 + \hat{\delta}_y^2\right) - 4 \hat{u}_x \hat{\delta}_x = -2 \xi \left(\bar{T}_* + \bar{T}_y \hat{\delta}_y\right) \left(1 + \hat{\delta}_y^2\right)^{1/2}$$  \hspace{1cm} (25)

where $M = \gamma \Delta T \bar{v}_0 / (2 \rho \kappa \Delta \bar{\eta})$ is the Marangoni number. In Eq. (6), the mass flux is non-dimensionalized as

$$K \hat{J} = \hat{T}$$  \hspace{1cm} (26)

where $K = (kT/\rho \kappa \Delta \bar{\eta} \Delta \bar{\eta}) / (2 \rho \kappa \Delta \bar{\eta} M)$ is a parameter measuring the degree of non-equilibrium at the evaporating interface.

2.2. Long-wave evolution theory

By assuming the dependent variables of the non-isothermal evaporating layer vary slowly along the longitudinal direction, the long-wave theory can be employed to characterize the film dynamics [28]. In accordance with the lubrication theory, a small parameter $\lambda$ is denoted as the wave number and the governing equations are rescaled by the non-dimensional variables: $\xi = \lambda x$ and $\eta = \bar{y} / \bar{y}$. The order of magnitude of the dependent variables is set as follows: $u, J, \bar{T} = O(1)$ and $\bar{p}, \bar{\Pi} = O(\lambda^{-1})$. The film thickness $\delta(\xi)$ is considered as an unspecified unit-order function. For the sake of continuity, we set $v = O(\lambda)$. As $\lambda \rightarrow 0$, the dependent variables are expanded in powers of $\lambda$ as [29]

$$\begin{align*}
\hat{u} &= \hat{u}_0 + \lambda \hat{u}_1 + \cdots \\
\hat{v} &= \lambda (\hat{v}_0 + \lambda \hat{v}_1 + \cdots) \\
\hat{J} &= \hat{J}_0 + \lambda \hat{J}_1 + \cdots \\
\bar{T} &= \bar{T}_0 + \lambda \bar{T}_1 + \cdots \\
\bar{p} &= \lambda^{-1} (\bar{p}_0 + \lambda \bar{p}_1 + \cdots) \\
\bar{\Pi} &= \lambda^{-1} (\bar{\Pi}_0 + \lambda \bar{\Pi}_1 + \cdots)
\end{align*}$$  \hspace{1cm} (27)

By executing the asymptotic analysis, expansions (27) are substituted into the governing equations where the coefficients of like powers of $\lambda$ in each equation and boundary condition are equated to zero. Thus, the governing equations are achieved as

$$\begin{align*}
-\bar{P}_0 \beta_x + \bar{u}_{0\beta_x} &= 0 \\
-\bar{P}_0 \beta_y &= 0 \\
\bar{u}_{0\beta_x} + \bar{v}_{0\beta_y} &= 0 \\
\bar{T}_{0\beta_y} &= 0
\end{align*}$$  \hspace{1cm} (28) (29) (30) (31)

Following this, the dimensionless groups are related to $\lambda$ as

$$\begin{align*}
(A, B, E, M, S) &= \left(\lambda \bar{\Lambda}_0, \lambda \bar{\Lambda}_1, \bar{E}, \lambda \bar{M}, \bar{S} \lambda^{-3}\right)
\end{align*}$$  \hspace{1cm} (32)

where the order magnitudes of the dimensionless groups are set as follows: $A$ and $B = O(\lambda^{-1}), E = O(\lambda)$ to include the mass loss, $M = O(\lambda^{-1})$ to retain the thermocapillary effect in shear stress condition, and $S = O(\lambda^{-3})$ to retain the surface tension effect in normal stress condition, while $K$ and $P = O(1)$. The quantities with over-bar are of unit order of magnitude as $\lambda \rightarrow 0$. The boundary conditions incorporating with the dimensionless groups at the interface can be expressed as

$$\begin{align*}
j_0 &= -\bar{u}_0 \beta_x + \bar{v}_0 \\
\hat{J}_0 &= -\bar{T}_0 \\
-\bar{P}_0^{(v)} + \bar{P}_0 &= -\bar{S} \beta_x + \bar{A} \beta_x^{-3} + \bar{B} \beta_x^{-5/3} \\
\bar{u}_{0\eta} &= -2 \xi \bar{M}^{-1} \left(\bar{T}_0 \beta_x + \bar{T}_0 \beta_y \beta_x\right) \\
\bar{K} j_0 &= \bar{T}_0
\end{align*}$$  \hspace{1cm} (33) (34) (35) (36) (37)

Eq. (35) is yielded from Eq. (24), with the term $\bar{S} = 2 \lambda^2 \bar{M}^{-1}$ being eliminated. It is observed that the thermocapillary effect which is represented by the Marangoni number, $M$ does not appear at leading order in the normal stress balance, but it is retained in the shear stress balance as depicted in Eq. (36). At the wall ($\eta = 0$), the boundary conditions are treated as no-slip condition and constant wall temperature,

$$\begin{align*}
\hat{u}_0 &= 0 \\
\bar{V}_0 &= 0 \\
\bar{T}_0 &= 1
\end{align*}$$  \hspace{1cm} (38)

The governing Eqs. (28)–(31) are solved together with the list of corresponding boundary conditions (33)–(38) to generate a long-wave evolution equation which governs the thin liquid film thickness distribution with evaporation and thermocapillary convection effects. Eq. (31) is solved together with the conditions in Eqs. (34), (37) and (38) to yield the liquid temperature distribution

$$\begin{align*}
\bar{T}_0 &= 1 - \left(K + \beta_x\right)^{-1} \\
\bar{j}_0 &= \left(K + \beta_x\right)^{-1}
\end{align*}$$  \hspace{1cm} (39) (40)

The liquid pressure is obtained by solving Eq. (29), subject to condition (35), as

$$\begin{align*}
\bar{P}_0 &= \bar{P}_0^{(v)} - \bar{S} \beta_x + \bar{A} \beta_x^{-3} + \bar{B} \beta_x^{-5/3}\beta_x
\end{align*}$$  \hspace{1cm} (41)

After substituting Eq. (41) into Eq. (28) and applying the conditions in Eqs. (36) and (38), solving Eq. (28) yields the $x$-component of the liquid velocity as

$$\begin{align*}
\hat{u}_0 &= \beta_x \left(1 + \delta_x \eta\right) + 2 \xi \bar{M}^{-1} \left(K + \beta_x\right)^{-2} \delta_x \eta
\end{align*}$$  \hspace{1cm} (42)
where $\Phi = \left( \frac{S}{2} \delta^3 + 3\alpha - \frac{1}{2} \frac{\delta^2}{\varepsilon} \right)$. By substituting Eq. (42) into Eq. (30) and applying the condition in Eq. (38), y-component of the liquid velocity can be obtained as

$$v_y = -\phi_y \left( \frac{1}{6} y^3 - \frac{1}{2} \delta y^2 \right) + \frac{1}{2} \phi_y \delta^2 y^2 - \text{MP}^{-1} K \left( K + \delta \right) - \frac{2}{2} \left( \frac{1}{K + \delta} - 1 \right) \frac{1}{K^2} y^2 \quad (43)$$

By plugging Eqs. (40) and (42)–(43) into Eq. (33), we obtain the evolution equation which incorporates the effects of disjoining pressure and the thermocapillary convection as

$$-E \left( K + \delta \right)^{-1} \frac{2}{2} \left( \frac{1}{K + \delta} - 1 \right) \frac{1}{K^2} \delta \frac{\dot{\delta}}{4} \left( \delta^3 \left( S_{\text{max}} + A \delta^2 \right) + \frac{8}{3} \left( e^{-\delta} \right) \right) - \text{MP}^{-1} K \left( K + \delta \right) - \frac{2}{2} \left( \frac{1}{K + \delta} - 1 \right) \frac{1}{K^2} \delta^2 \frac{\dot{\delta}}{4} \left( \delta^3 \left( S_{\text{max}} + A \delta^2 \right) + \frac{8}{3} \left( e^{-\delta} \right) \right) = 0 \quad (44)$$

Eq. (44) is a fourth-order, nonlinear ordinary differential equation which can be solved numerically using the fourth-order Runge–Kutta Fehlberg method to yield the liquid film thickness in the evaporating thin film region. The numerical scheme is justified to produce accurate results with a sufficiently small relative error of $10^{-8}$. Four boundary conditions are required to solve Eq. (44), i.e., $\dot{\delta}(0)$, $\delta(0)$, $\delta(\infty)$, and $\delta_{\text{sat}}(0)$. The origin ($x = 0$) is set at the intersection of the adsorbed layer and the evaporating thin film region where the film thickness equals to the mean film thickness of adsorbed thin film region, $\delta_0$. Here, we take $\delta_0 = 10 \text{ nm}$. The first-order derivative of film thickness is set to be the initial slope of the wetting film with zero contact angles. On account of the evaporation suppression by the disjoining pressure, the film thickness is virtually flat and hence any value of $\dot{\delta}(0)$ which is below $10^{-11}$ justifies an invariant film profile [25]. On the other hand, to satisfy a far-field boundary condition, the second-order derivative is obtained with a shooting method [24,25,27]. The intersection of the evaporating thin film region and intrinsic meniscus region is identified as this far-field boundary setting. This second-order derivative is evaluated iteratively until it converges to the curvature of the intrinsic meniscus region. The radius of curvature (reciprocal of the mean curvature) of the intrinsic meniscus is assumed to approach a constant value, which is approximately half of the channel height for complete wetting of liquid on solid. The third-order derivative virtually induces no influence on the thin film profile and its initial value is set to be zero by assuming a flat adsorbed layer [33].

### 3.1. Field variables of working fluids

The evaporative heat transfer inherently interrelates with several field variables: liquid film thickness, liquid temperature, interfacial temperature, surface tension and evaporative mass flux across the interface. The distinctive thermo-physical properties of different types of working fluids engender variations on these field variables and hence the evaporative heat transfer characteristics between the models with and without taking into account the thermocapillary effect. Fig. 2 depicts the liquid film thickness of various working fluids along the x-axis. For an excess temperature of 5 K, all the liquid film thicknesses increase in the axial direction. Ammonia has the largest film thickness, followed by acetone, heptane and water, in a descending order. For the sake of comparison, it has also been shown that ammonia manifests the largest film thickness among those of acetone, pentane and octane, in a previous work employing nonpolar liquids without considering thermocapillary effect [12]. A pronounced deviation is induced by the thermocapillary effect on the film thickness such that the film thickness of Model 1 is larger than that of Model 2. As a consequence of temperature gradient, surface tension force is provoked in the opposite direction to the flow. Thus, the thermocapillary effect impedes the flow circulation and retards the evaporation rate [27]. When the thermocapillary effect is neglected, the absence of the opposing force reduces the film thickness and the evaporative heat transfer rate might be overrated.

The deviation between the two models increases from water to heptane, acetone, and ammonia. Therefore, it is expected that the thermocapillary effect incurred on ammonia is the most conspicuous, and it is in the successional order as that of the film thickness.

Fig. 3 depicts the contour plots of the magnitude of temperature gradient (VT) for acetone, ammonia, heptane and water at an excess temperature of 5 K and a liquid saturation temperature of 333 K. The heat input from the solid substrate is transferred to the liquid phase and taken up as the latent heat of evaporation at the liquid–vapor interface. Heat transfer occurs by convection from the hot fluid adjacent to the solid substrate at $T_w$ to the liquid–vapor interface at $T_{\text{sat}}$, in which the dimensionless form can be evaluated from Eq. (39) by setting $\eta = \delta$. Referring to Fig. 2, for the same longitudinal length, the liquid film thickness of water is the thinnest compared with that of others. Low thermal resistance is associated with small film thickness. Therefore, the liquid–vapor interfacial temperature of water is higher than that of other working fluids.

The transverse temperature variation of water is the smallest. We can observe that all the temperature gradients decrease gradually along the axial direction. Ammonia has the highest temperature gradient with the shortest evaporating film length, while water has the

![Fig. 2. Liquid film thickness along the axial direction of Model 1 (with thermocapillary effect) and Model 2 (without thermocapillary effect) for different types of working fluid.](image-url)
lowest temperature gradient with the longest evaporating film length, \( l_0 \), which extending from the contact line to the location where the film thickness is 30 times of \( l_0 \) [27]. The temperature gradient is found to be inversely proportional to the evaporating film length of the liquid film.

Fig. 4 depicts the liquid–vapor interfacial temperature profiles of different working fluids with an excess temperature of 5 K. The interfacial temperature decreases with the increment of the film thickness. The inverse relationship between the interfacial temperature and the liquid film thickness is attributable to the thermal resistance that increases with liquid film thickness. The highest axial temperature drop is observed in ammonia, followed by acetone, heptane and water in a descending order. Both models have the same interfacial temperature at the contact line when \( x = 0 \) and deviations are induced along the axial direction. The difference between the two models is mainly due to the deviation in the surface tension. The surface tension employed in Model 2 is intrinsically a constant while for Model 1, the surface tension which is a function of the liquid temperature, is dependent on the deviation in the surface tension. The surface tension variation in surface tension between the two models due to its high surface tension gradient and interfacial temperature. This indicates that both surface tension gradient and liquid temperature play a role in determining the surface tension of a working fluid. In summary, it has been shown that the interfacial temperature of a working fluid is highly dependent on the liquid film thickness, which is in turn intrinsically affected by the thermo-physical properties of a working fluid. In what follows, we focus on the analysis of thermal performance of different working fluids with the incorporation of thermocapillary effect.

3.2. Evaporative heat transfer characteristics

The evaporative heat transfer is intimately associated with the liquid temperature distribution. Fig. 6 depicts the contour plots of the magnitude of heat flux of the liquid film for the four working fluids. The magnitude of heat flux is evaluated as \( |q'| = |k\nabla T| \). We can observe that the heat flux magnitude decreases gradually along the axial direction and the heat flux magnitude is the highest at the evaporating thin film where the liquid film is the thinnest. Among these working fluids, ammonia portrays the highest temperature gradient and heat flux magnitude with the shortest evaporating film. Comparing to Fig. 3, the heat flux magnitude is distinguished from the temperature gradient by a multiplication with a factor of liquid thermal conductivity. In this case, the increasing order of heat flux magnitude of each working fluid is manifested in the same sequence that the surface tension gradient follows, as depicted in Table 1. On the other hand, the temperature gradient magnitude shows the same ascending order that the film thickness and the liquid–vapor interfacial temperature manifests in Figs. 2 and 4, respectively.

Fig. 7 depicts the evaporative mass flux, \( J \), of different working fluids in the axial direction with an excess temperature of 5 K. The evaporative

![Fig. 3. Liquid temperature gradient magnitude contours of Model 1 for acetone, ammonia, heptane, and water at an excess temperature of 5 K.](image)

![Fig. 4. Variations of liquid–vapor interfacial temperature along the axial direction for different working fluids of Model 1 and Model 2, at an excess temperature of 5 K.](image)

![Fig. 5. Surface tension gradient of various working fluids.](image)
mass flux shows a maximum value at the contact line and decreases along the axial direction due to the increasing thermal resistance when the film thickness increases. Ammonia has the largest evaporation rate, followed by acetone, heptane and water. It can be observed that the evaporation rate is impeded by the thermocapillary flow. This can be clearly seen in ammonia where both models display evident discrepancy in the evaporative mass flux even at a sufficiently small excess temperature. Thermocapillary effect is often neglected when the excess temperature is less than 10 K or the Marangoni number is typically small \[33\]. By referring to Figs. 3 and 7, we can conclude that the significance of thermocapillary effect in the evaporation rate corresponds to the magnitude of temperature gradient. Higher temperature gradient magnitude yields larger deviation between the two models. Apart from evaporative mass flux, the evaporative heat flux can also be evaluated as \[ q_e = JL \text{.} \] In accordance with Fig. 7, Fig. 8 exhibits the evaporative heat flux in the axial direction for different working fluids with an excess temperature of 5 K. The evaporative heat flux is highly dependent on the latent heat of vaporization. Again, ammonia possesses the highest evaporative heat flux among the four working fluids. Compared to the evaporative mass flux, the evaporative heat flux of water exceeds that of heptane due to its higher latent heat of vaporization.

Fig. 9 depicts the variations of total evaporation rate as a function of excess temperature for different working fluids. The total evaporation rate which is defined as \[ J_c = \int q_e \, dx \text{,} \] increases with increasing excess temperature. The evaporation rate of Model 2 is higher than that of Model 1 showing that the existence of thermocapillary effect inhibits the evaporation heat transfer as the liquid is being pulled back to the intrinsic meniscus region and restrained from flowing to the evaporating thin film region where intense evaporation takes place. The discrepancy between the two models increases with the excess temperature. Ammonia shows the highest discrepancy among other working fluids while that of water is the smallest. This shows that the significance of thermocapillary effect varies according to the type of working fluid. It can be explicitly observed that the varying degrees of significance are invariably associated with the temperature gradient magnitude of liquid when we compare the discrepancy between both models in Fig. 9 with the temperature gradient magnitude in Fig. 3. This justifies that the thermocapillary convection is attributed to the existence of temperature gradient.

In Fig. 10(a), the total evaporative heat transfer rate over the evaporating film length, \[ q_e = \int q_e \, dx \text{,} \] is plotted as a function of excess temperature. The evaporative heat transfer rate increases from heptane, acetone, water, to ammonia. The discrepancy between the two models and hence the significance of thermocapillary effect follow the same order. It has been shown in a previous study by Lim and Hung [27] that the thermocapillary effect of heptane should not be simply ignored in the heat transfer analysis of an evaporating thin film due to its significance under certain conditions. However, we can observe from
that the significance of thermocapillary effect of heptane is the smallest. The thermocapillary effect is more prominent in other working fluids. Therefore, this further verifies the importance of considering the thermocapillary effect in the heat transfer analysis of an evaporating thin film. To compare the significance of thermocapillary effect among the working fluids, we define a ratio which is given by $\psi = q_c,1/q_c,2$. Fig. 10(b) plots this ratio as a function of excess temperature for different types of working fluids. The ratio $\psi$ is the relative value of Model 1 compared to that of Model 2. The difference between Model 1 and Model 2 increases when the excess temperature increases. At a high excess temperature of $\Delta T = 50$ K, the difference between the models amounts more than 50% for ammonia while that of water displays a maximum difference of 25%, which is the lowest among others. The ascending order of this difference is in accordance with that of the temperature gradient magnitude in Fig. 3. The significance of thermocapillary effect is dominated by the effect of temperature gradient. The thermocapillary effect is attributed to the presence of a gradient in surface tension which leads to a reverse flow from the evaporating thin film to the intrinsic meniscus region. This surface tension gradient is dominantly governed by the presence of temperature gradient. For different types of working fluid under the same operating conditions, the variations of thermo-physical properties induce different magnitudes of temperature gradient in the liquid phase and hence leading to different degrees of thermocapillary effect.

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4. Concluding remarks

The impact of thermocapillary effect induced by different types of working fluid is elucidated. We employ the long-wave evolution theory to derive a two-dimensional mathematical model based on the first principles. By comparing the models with and without thermocapillary effect for different types of working fluid, it can be observed that the evaporative mass and heat transfer rate are overrated when the thermocapillary effect is neglected and the overestimates increase with increasing excess temperature. The discrepancy between the two models indicates the significance of thermocapillary effect which varies according to the type of working fluid. It can be explicitly observed that the varying degrees of significance are invariably associated with the temperature gradient magnitude of working fluid, justifying that the thermocapillary convection is attributed to the presence of temperature gradient. The surface tension gradient which provokes thermocapillary flow is dominantly governed by the presence of temperature gradient. For different types of working fluid under the same operating conditions, the variations of thermo-physical properties induce different temperature gradient magnitudes in the liquid phase and hence incurring different degrees of thermocapillary effect on the heat transfer characteristics. Therefore, we conclude that the thermocapillary effect cannot be simply neglected in the heat transfer analysis of an evaporating thin film, particularly at high excess temperature. The thermocapillary disparities among different types of working fluid are dominantly governed by the presence of temperature gradient.
fluid are explicitly observed. While the thermocapillary effect has long been ignored, it can be evidenced that even at a small excess temperature, acute errors can be incurred for certain types of working fluid in the thermal analysis of an evaporating thin liquid film.

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References


