Pergamon

Int. J. Heat Mass Transfer. Vol. 41, No. 15, pp. 2321–2334, 1998
© 1998 Elsevier Science Ltd. All rights reserved
Printed in Great Britain
0017–9310/98 $19.00+0.00

PII: S0017-9310(97)00330-X

A general correlation for pool film boiling heat transfer from a horizontal cylinder to saturated binary liquid mixtures

MING-HUEI LIU, YU-MIN YANG† and JER-RU MAA
Department of Chemical Engineering, National Cheng Kung University, Tainan, Taiwan 70101, R.O.C.

(*Received* 18 *April* 1997 *and in final form* 24 *October* 1997)

Abstract—An approximate analytical solution of theoretical pool film boiling model of binary mixtures without radiation effect is derived by using an integral method. By including radiative contribution through a radiation parameter, a general correlation for predicting pool film boiling heat transfer coefficient of binary mixtures over horizontal cylinder is then proposed. As examined by five nonazeotropic and azeotropic binary systems, the predictions by this general correlation are shown to agree well with the rigorous numerical results. Furthermore, the proposed correlation is given an advantage over previous correlations in that it predicts also the extent of the mass diffusion effect on pool film boiling heat transfer of binary mixtures. © 1998 Elsevier Science Ltd. All rights reserved.

1. INTRODUCTION

The theories for laminar film boiling of single component liquids have been well documented in several review articles for example, Jordan [1], Kalinin *et al.* [2], Lienhard and Witte [3], and Sakurai [4]. Even the turbulent film boiling has also been subjected to treatment by several investigators [5]. Nevertheless, film boiling of liquid mixtures has virtually been ignored regardless of its importance in the chemical and process industries. A few of the experimental and theoretical studies, which are available in the literature, on film boiling of binary liquid mixtures have been reviewed by Liu *et al.* [6]. Both the experimental and theoretical results evidenced the importance of mass diffusion in film boiling of binary liquid mixtures.

In the practical applications the boiling heat transfer of binary mixtures is one of the most important items to be assessed beforehand. However, there have only been limited success in the prediction of the film boiling heat transfer coefficient of mixtures. This indeed results from the complicated transport phenomena encountered in liquid mixtures. In our previous paper [7], a simple correlation for predicting pool film boiling heat transfer coefficient h of binary mixtures was proposed as

$$h = h_{\mathrm{id}}(1+F)^n \tag{1}$$

where h_{id} is the ideal heat transfer coefficient of binary mixture

$$h_{\mathrm{id}} = h_1(1-x)+h_2x \tag{2}$$

defined from a linear mixing law for pure components. In equation (2) h_1 and h_2 are the heat transfer coefficients of pure component 1 and pure component 2, respectively, at the specified wall superheat. And F is a mass diffusion factor defined by the following equation:

$$F = (x-y)\left(\frac{\alpha_{\mathrm{L}}}{D_{\mathrm{L}}}\right)^{1/2}\left(\frac{C_{p\mathrm{L}}}{h_{\mathrm{LV}}}\right)\left(\frac{\mathrm{d}T}{\mathrm{d}x}\right) \tag{3}$$

which attempts to account for the effect of mass transfer processes in binary liquid mixtures on film boiling heat transfer.

Equation (1) is attractive in that boiling heat transfer coefficients of binary mixtures can be conveniently predicted from that of pure components with the mass diffusion effect also to be assessed. However, equation (1) is suffering from the empirical determination of n for each binary system. The values of n should be determined empirically by best fitting based on experimental data or numerical results. For example, it was found that $n = 0.27$ for ethylene oxide/water and $n = 0.19$ for ethanol/benzene, which results in an average error of 2.1 and 0.5% as compared with the numerical results for the respective binary system. Therefore, while equation (1) was shown to predict the film boiling heat transfer coefficient of binary mixtures from those of pure components quite satisfactorily, it is most desirable that a more useful general correlation with much physical meaning can be developed instead.

In this work, an approximate analytical solution of theoretical pool film boiling model without radiation effect is derived firstly by using an integral method.

---

† Author to whom correspondence should be addressed. Tel.: 886 6 275 7575 x62633. Fax: 886 6 234 4496. E-mail: ymyang@mail.ncku.edu.tw.

NOMENCLATURE

C_p	heat capacity [J kg^{-1} K^{-1}]
D	diameter of cylinder heater [m]
D_L	diffusion coefficient of liquid phase [m^2 s^{-1}]
F	mass diffusion factor defined by equation (3)
F_M	modified mass diffusion factor defined by equation (45)
h	heat transfer coefficient [W m^{-2} K^{-1}]
H	effective latent heat of vaporization [J kg^{-1}]
h_{LV}	latent heat of vaporization [J kg^{-1}]
k	thermal conductivity [W m^{-1} K^{-1}]
m	mass flux [kg m^{-2} s^{-1}]
Pr	Prandtl number
q	heat flux [kW m^{-2}]
r	radius of cylinder heater [m]
S	dimensionless group defined by equation (43)
Sc	Schmidt number
T	temperature [K]
u	velocity component in x-direction [m s^{-1}]
v	velocity component in y-direction [m s^{-1}]
w	mass fraction
w^*	mass fraction in vapor phase at equilibrium
x	mass fraction in bulk liquid; coordinate along the heater surface [m]
y	mass fraction in vapor phase at equilibrium; coordinate normal to the heater surface [m].

Greek symbols

α	thermal diffusivity [m^2 s^{-1}]
α_A	radiation absorptivity of liquid
δ	thickness of vapor film and boundary layer [m]
ΔT	superheat [K]
ε	radiation emissivity
θ	angle [°]
μ	viscosity [kg m^{-1} s^{-1}]
ν	kinematic viscosity [m^2 s^{-1}]
ξ	boundary layer thickness ratio
ρ	density [kg m^{-3}]
σ	Stefan–Boltzmann constant [W m^{-2} K^{-4}].

Subscripts

1, 2	component 1, 2
ave	average
az	azeotrope
b	liquid bulk
co	convection
id	ideal
i	vapor–liquid interface
L	liquid phase
M	mass
mix	binary mixture
r	radiation
sat	saturated
T	thermal
V	vapor phase
W	wall surface; vapor.

The approximate analytical solution with radiation effect which is necessary as a basic equation for a general correlation then results from including radiative contribution through a radiation parameter. On the other hand, a rigorous solution of the theoretical pool film boiling model with radiation effect is also obtained numerically. This enables one to verify the accuracy of the proposed general correlation by comparing its prediction with the rigorous numerical solution. Five binary systems—including ethanol/benzene, ethylene oxide/water, methanol/water, ethanol/water, and n-propanol/water—under atmospheric pressure are chosen for illustrating different degrees of the mass diffusion effect of binary mixtures on pool film boiling heat transfer.

2. THEORETICAL ANALYSIS

Pool film boiling from a horizontal cylinder is characterized by the existence of continuous vapor film surrounding the heated surface. Bubbles depart from the top part of the cylinder. Furthermore, in the boiling of binary mixtures, the heat transfer and the mass transfer processes are closely linked. Figure 1 shows schematically the physical model and coordinates. Although such assumptions may be applicable for limited cases in film boiling [7, 8], this model assumes that there exists a smooth vapor–liquid interface and the so-called boundary layer approximation can be employed for the two-phase boundary layer (TPBL) theory. A rigorous solution, which can only be obtained numerically, and an approximate analytical solution, which is derived by employing the integral analysis as used by von Karman for the hydrodynamic boundary layer, will be described in this section.

2.1. *Rigorous numerical solution*

A rigorous numerical solution of a theoretical model based on laminar two-phase boundary layer

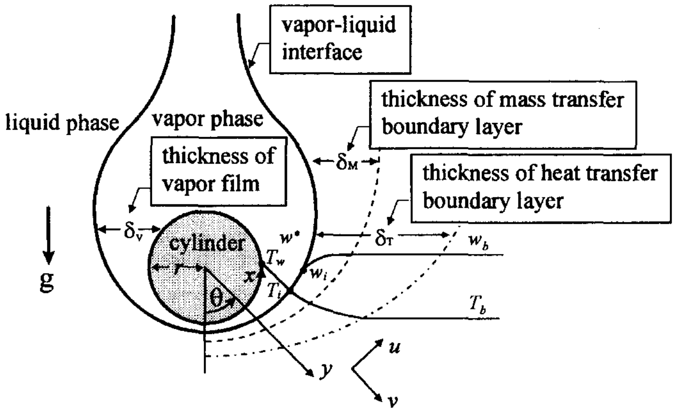

Fig. 1. Physical model and coordinates for pool film boiling of binary mixture over horizontal cylinder.

theory for pool film boiling heat transfer from a horizontal cylinder of radius r to saturated binary liquid mixtures including the radiation effect has ever been obtained. The details of the mathematical formulation and solution procedure can be seen elsewhere [9]. For the sake of completeness, however, the basic governing equations and interface and boundary conditions are summarized as follows.

Vapor phase

$$\text{Continuity:}\quad \frac{\partial u_V}{\partial x}+\frac{\partial v_V}{\partial y}=0 \tag{4}$$

$$\text{Momentum:}\quad u_V\frac{\partial u_V}{\partial x}+u_V\frac{\partial u_V}{\partial y} = \nu_V\frac{\partial^2 u_V}{\partial y^2}+\frac{g\sin\theta(\rho_b-\rho_V)}{\rho_V} \tag{5}$$

$$\text{Energy:}\quad u_V\frac{\partial T_V}{\partial x}+u_V\frac{\partial T_V}{\partial y}=\frac{k_V}{\rho_V C_{pV}}\frac{\partial^2 T_V}{\partial y^2}. \tag{6}$$

Liquid phase

$$\text{Continuity:}\quad \frac{\partial u_L}{\partial x}+\frac{\partial v_L}{\partial y}=0 \tag{7}$$

$$\text{Momentum:}\quad u_L\frac{\partial u_L}{\partial x}+v_L\frac{\partial u_L}{\partial y} = \nu_L\frac{\partial^2 u_L}{\partial y^2}+\frac{g\sin\theta(\rho_b-\rho_L)}{\rho_L} \tag{8}$$

$$\text{Energy:}\quad u_L\frac{\partial T_L}{\partial x}+v_L\frac{\partial T_L}{\partial y}=\frac{k_L}{\rho_L C_{pL}}\frac{\partial^2 T_L}{\partial y^2} \tag{9}$$

$$\text{Conservation of species:}\quad u_L\frac{\partial w_{2L}}{\partial x}+v_L\frac{\partial w_{2L}}{\partial y} = D_L\frac{\partial^2 w_{2L}}{\partial y^2}. \tag{10}$$

Interface and boundary conditions

$$y=0,\quad u_V=u_V=0,\quad T_V=T_W \tag{11}$$

$$y=\delta_V,\quad T=T_i,\quad w_{2Vi}=w'_{2i}(T_i),\quad w_{2Li}=w_{2i}(T_i) \tag{12}$$

$$u_{Vi}=u_{Li},\quad \mu_V\left(\frac{\partial u_V}{\partial y}\right)_i=\mu_L\left(\frac{\partial u_l}{\partial y}\right)_i \tag{13}$$

$$\left(\rho_V u_V\frac{d\delta}{dx}-\rho_V u_V\right)_i=\left(\rho_L u_L\frac{d\delta}{dx}-\rho_L v_L\right)_i \tag{14}$$

$$m_{2Vi}=\rho_L D_L\left(\frac{\partial w_{2L}}{\partial y}\right)_i+w_{2Li}(m_1+m_2)_{Li} \tag{15}$$

$$-k_V\left(\frac{\partial T_V}{\partial y}\right)_i+q_{rc}=(m_1+m_2)h_{LV}-k_L\left(\frac{\partial T_L}{\partial y}\right)_i \tag{16}$$

$$y=\infty,\quad u_L=v_L=0,\quad w_{2L}=w_{2b},\quad T_L=T_b. \tag{17}$$

2.2. *Approximate analytical solution*

The above mentioned rigorous solution can only be obtained numerically. However, it is desirable to derive an approximate analytical solution which is necessary as a basic equation for a general correlation for pool film boiling heat transfer in binary liquid mixtures. The theory employed here is based on major assumptions made by Bromley [10], and Sakurai *et al.* [11] in their analyses of pool film boiling heat transfer for single-component liquids. Therefore, the following theory for binary mixtures may be viewed as an extension of their works.

The pool film boiling heat transfer coefficient for binary liquid mixtures h_{mix} is expressed by the equation

$$h_{mix}=h_{co,mix}+Jh_r \tag{18}$$

where $h_{co,mix}$ is the pool film boiling heat transfer coefficient without a radiation effect at the same cylinder surface superheat, J is a radiation parameter, and h_r is a radiation heat transfer coefficient for parallel plates.

2.2.1. *Heat transfer coefficient without radiation effect*

Assumptions

The following assumptions are made in the theoretical pool film boiling model based on laminar two-phase boundary layer theory to obtain the approximate analytical solution in a simple form.

(1) Inertia forces and convective energy transports of vapor and liquid, and body force and convective mass transports in the liquid are neglected to get the velocity, temperature, and concentration distributions.

(2) The mass diffusion equation for the vapor phase is omitted.

(3) The radiation effect is omitted.

(4) The effect of superheat in vapor phase is compensated for by replacing the latent heat of vaporization h_{LV} with an effective latent heat of vaporization H [1].

$$H = h_{LV}(1+0.4C_{pV}\Delta T_V/h_{LV})^2 \tag{19}$$

where ΔT_V ($= T_W - T_i$) is the temperature gradient in the vapor film.

(5) The dimensionless heat transfer and mass transfer boundary layer thicknesses, $\xi_T = \delta_T/\delta_V$ and $\xi_M = \delta_M/\delta_V$, are assumed to be independent of the coordinate x along the heater surface. And noticing the similarity in differential equations and boundary conditions, the relation between the thermal and concentration boundary layers in laminar flow is assumed to be given by

$$\xi_T/\xi_M = Sc_L^{1/3}/Pr_L^{1/3}. \tag{20}$$

Equation (20) results from the well known Pohlhausen's solution for convective heat transfer and the analogy between energy and mass transfer.

(6) The bulk liquid surrounding the tube is assumed stagnant, i.e.

$$u_b = 0. \tag{21}$$

(7) The velocity boundary conditions are assumed to be the no-slip condition at the wall and at the vapor–liquid interface.

Basic equations

For the vapor boundary layer, momentum conservation and energy conservation, respectively, take the form

$$g\sin\theta(\rho_b - \rho_V) + \mu_V\frac{\partial^2 u_V}{\partial y_V^2} = 0 \tag{22}$$

$$k_V\frac{\partial^2 T_V}{\partial y_V^2} = 0. \tag{23}$$

For the liquid boundary layer, an additional mass conservation is involved

$$k_L\frac{\partial^2 T_L}{\partial y_L^2} = 0 \tag{24}$$

$$D_L\frac{\partial^2 w_L}{\partial y_L^2} = 0. \tag{25}$$

The boundary and interface conditions are as follows:

$$y_V = 0, \quad u_V = u_V = 0, \quad T_V = T_W \tag{26}$$

$$y_V = \delta_V(y_L = 0), \quad u_{Vi} = 0 \tag{27}$$

$$T_V = T_L = T_i \neq T_b \tag{28}$$

$$w_{2Vi} = w_{2i}^*(T_i), \quad w_{2Li} = w_{2i}(T_i) \tag{29}$$

$$m_{2Vi} = \rho_L D_L\left(\frac{\partial w_{2L}}{\partial y}\right)_i + w_{2Li}(m_1+m_2)_{Li} \tag{30}$$

$$y_L \geqslant \delta_T, \quad T_L - T_b \tag{31}$$

$$y_L \geqslant \delta_M, \quad w_{2L} = w_{2b}. \tag{32}$$

It should be noted that the interface temperature is usually different from saturation temperature of the binary liquid mixture as shown by equation (28), except for the azeotrope. Furthermore, equation (30) represents the mass balance of component two of the binary mixture at the interface.

The governing equations may now be solved completely in terms of the unknowns δ_V, δ_T and δ_M. The results are

$$u_V = \frac{g(\rho_b - \rho_V)\delta_V^2\sin\theta}{2\mu_V}\left[\left(\frac{y_V}{\delta_V}\right) - \left(\frac{y_V}{\delta_V}\right)^2\right] \tag{33}$$

$$T_V = T_W - \Delta T_V\left(\frac{y_V}{\delta_V}\right) \tag{34}$$

$$T_L = T_i - \Delta T_L\left(\frac{y_L}{\delta_L}\right) \tag{35}$$

$$w_L = w_{2Li} - \Delta w_{2L}\left(\frac{y_L}{\delta_M}\right) \tag{36}$$

where $\Delta T_V = T_w - T_i$, $\Delta T_L = T_i - T_b$, and $\Delta w_{2L} = w_{2i} - w_{2b}$. The model implies linear temperature and concentration profiles, but a quadratic vapor velocity profile.

Vapor film thickness

Next, integral heat balance is performed on the vapor layer, giving

$$H\frac{d}{dx}\int_0^{\delta_{V,mix}} u_L\rho_V\,dy = -k_L\frac{dT_L}{dy_L}\bigg|_{y_L=0} + k_L\frac{dT_L}{dy_L}\bigg|_{y_L=0}. \tag{37}$$

The second term in the right-hand side of equation (37) represents an additional heat conducted from the interface into the bulk liquid owing to higher interface temperature than bulk liquid temperature resulting from preferential evaporation of the more volatile component at the vapor–liquid interface.

Similarly, integral mass balance is performed on the vapor layer, giving

$$\frac{\mathrm{d}}{\mathrm{d}x}\int_0^{\delta_{\mathrm{L}}} u_{\mathrm{L}}\rho_{\mathrm{V}}\,\mathrm{d}y = m_1 + m_2 = -\frac{\rho_{\mathrm{L}}D_{\mathrm{L}}}{w_{2\mathrm{L}i}-w_{2\mathrm{V}i}}\left(\frac{\mathrm{d}w_{2\mathrm{L}}}{\mathrm{d}y_{\mathrm{L}}}\right)_i. \tag{38}$$

Substituting equations (33)–(35) into equation (37) yields

$$\frac{\mathrm{d}}{\mathrm{d}x}[\delta_{\mathrm{V,mix}}\sin^{1/3}\theta]^3 = \left[\frac{12\mu_{\mathrm{V}}k_{\mathrm{V}}\Delta T_{\mathrm{V}}}{g\rho_{\mathrm{V}}(\rho_{\mathrm{b}}-\rho_{\mathrm{V}})H} - \frac{12\mu_{\mathrm{V}}k_{\mathrm{L}}\Delta T_{\mathrm{L}}}{g\rho_{\mathrm{V}}(\rho_{\mathrm{b}}-\rho_{\mathrm{V}})H\xi_{\mathrm{T}}}\right]\frac{1}{\delta_{\mathrm{V,mix}}} \tag{39}$$

and substituting equations (33) and (36) into equation (38) yields

$$\frac{\mathrm{d}}{\mathrm{d}x}[\delta_{\mathrm{V,mix}}\sin^{1/3}\theta]^3 = \left[\frac{12\mu_{\mathrm{V}}k_{\mathrm{L}}\Delta T_{\mathrm{L}}}{g\rho_{\mathrm{V}}(\rho_{\mathrm{b}}-\rho_{\mathrm{V}})H\xi_{\mathrm{T}}}\,\frac{Pr_{\mathrm{L}}}{Sc_{\mathrm{L}}}\,\frac{\xi_{\mathrm{T}}}{\xi_{\mathrm{M}}}\,\frac{H}{C_{\mathrm{pL}}}\,\frac{\dfrac{\Delta w_{2\mathrm{L}}}{w_{2\mathrm{L}i}-w_{2\mathrm{V}i}}}{\Delta T_{\mathrm{L}}}\right] \times \frac{1}{\delta_{\mathrm{V,mix}}}. \tag{40}$$

The solutions to equations (39) and (40), respectively, are

$$\delta_{\mathrm{V,mix}} = S(\theta)\left[\frac{12\mu_{\mathrm{V}}k_{\mathrm{V}}\Delta T_{\mathrm{V}}r}{g\rho_{\mathrm{V}}(\rho_{\mathrm{b}}-\rho_{\mathrm{V}})H} - \frac{12\mu_{\mathrm{V}}k_{\mathrm{L}}\Delta T_{\mathrm{L}}r}{g\rho_{\mathrm{V}}(\rho_{\mathrm{b}}-\rho_{\mathrm{V}})H\xi_{\mathrm{T}}}\right]^{1/4} \tag{41}$$

and

$$\delta_{\mathrm{V,mix}} = S(\theta)\left[\frac{12\mu_{\mathrm{V}}k_{\mathrm{L}}\Delta T_{\mathrm{L}}r}{g\rho_{\mathrm{V}}(\rho_{\mathrm{b}}-\rho_{\mathrm{V}})H\xi_{\mathrm{T}}}\left(\frac{Pr_{\mathrm{L}}}{Sc_{\mathrm{L}}}\right)^{2/3} \times \frac{H}{C_{\mathrm{pL}}}\,\frac{\dfrac{\Delta w_{2\mathrm{L}}}{w_{2\mathrm{L}i}-w_{2\mathrm{V}i}}}{\Delta T_{\mathrm{L}}}\right]^{1/4} \tag{42}$$

where

$$S(\theta) = \left[\frac{4}{3}\frac{\int \sin^{1/3}\theta\,\mathrm{d}\theta}{\sin^{4/3}\theta}\right]^{1/4}. \tag{43}$$

By combining equations (41) and (42), one obtains

$$\delta_{\mathrm{V,mix}} = S(\theta)\left[\frac{12\mu_{\mathrm{V}}k_{\mathrm{V}}\Delta_{\mathrm{V}}r}{g\rho_{\mathrm{V}}(\rho_{\mathrm{b}}-\rho_{\mathrm{V}})H(1+F_{\mathrm{M}})}\right]^{1/4} \tag{44}$$

where the modified F factor, F_{M}, is given by

$$F_{\mathrm{M}} = (w_{2\mathrm{L}i}-w_{2\mathrm{V}i})\left(\frac{Sc_{\mathrm{L}}}{Pr_{\mathrm{L}}}\right)^{2/3}\frac{C_{\mathrm{pL}}}{H}\left(\frac{\Delta T_{\mathrm{L}}}{\Delta w_{2\mathrm{L}}}\right) \tag{45}$$

$$\simeq \frac{F(Sc_{\mathrm{L}}/Pr_{\mathrm{L}})^{1/6}}{(1+0.4C_{\mathrm{pV}}\Delta T_{\mathrm{V}}/h_{\mathrm{LV}})^2}. \tag{46}$$

The details of the derivation of equation (46) from equation (45) are given in the Appendix. In equation (46), F is given by equation (3).

Heat transfer equation

Turning now to evaluation of the average heat flux and heat transfer coefficient from the horizontal cylinder surface is

$$q_{\mathrm{co,mix}} = \frac{1}{2\pi r}\int_0^{\pi} 2r\frac{k_{\mathrm{V}}\Delta T_{\mathrm{V}}}{\delta_{\mathrm{V,mix}}}\,\mathrm{d}\theta = 0.512\Delta T_{\mathrm{V}}\left[\frac{k_{\mathrm{V}}^3 g\rho_{\mathrm{V}}(\rho_{\mathrm{b}}-\rho_{\mathrm{V}})H}{\mu_{\mathrm{V}}\Delta T_{\mathrm{V}}D}(1+F_{\mathrm{M}})\right]^{1/4} \tag{47}$$

and

$$h_{\mathrm{co,mix}} = \frac{q_{\mathrm{co,mix}}}{\Delta T_{\mathrm{W}}} = 0.512\frac{\Delta T_{\mathrm{V}}}{\Delta T_{\mathrm{W}}}\left[\frac{k_{\mathrm{V}}^3 g\rho_{\mathrm{V}}(\rho_{\mathrm{b}}-\rho_{\mathrm{V}})H}{\mu_{\mathrm{V}}\Delta T_{\mathrm{V}}D}(1+F_{\mathrm{M}})\right]^{1/4}. \tag{48}$$

It is interesting to note that the coefficient 0.512 is resulting from the assumption of no-slip condition at the vapor–liquid interface. If the liquid is assumed to move completely freely with the vapor, i.e. for zero shear condition at the vapor–liquid interface, it can be shown that the coefficient will have a value of 0.724.

In equation (48), ΔT_{V} represents the temperature difference between heated wall and vapor–liquid interface, i.e., $T_{\mathrm{W}}-T_i$. However, T_i is unknown *a priori* and has to be obtained as a result of the numerical solution mentioned above. In order to propose a useful predicting equation for heat transfer coefficient, therefore, it is most desirable that ΔT_{V} can be replaced by another suitable controlled operating variable. As shown in Fig. 3 for example, the rigorous numerical solutions reveal that the interface superheats ($T_i - T_{\mathrm{sat}}$) are usually much less than 30 K at wall superheat $\Delta T_{\mathrm{W}} = T_{\mathrm{w}} - T_{\mathrm{sat}} = 550$ K for the five binary systems studied in this work. If ΔT_{V} in equation (48) is replaced by ΔT_{W}, the resulting error in $h_{\mathrm{co,mix}}$ should be less than 5%. Therefore, the more convenient equation for calculation is postulated as

$$h_{\mathrm{co,mix}} \simeq 0.512\left[\frac{k_{\mathrm{V}}^3 g\rho_{\mathrm{V}}(\rho_{\mathrm{b}}-\rho_{\mathrm{V}})H}{\mu_{\mathrm{V}}\Delta T_{\mathrm{W}}D}(1+F_{\mathrm{M}})\right]^{1/4} \tag{49}$$

and the modified F factor given by equation (46), in the same reasoning, can then be approximately represented as

$$F_{\mathrm{M}} \simeq \frac{F(Sc_{\mathrm{L}}/Pr_{\mathrm{L}})^{1/6}}{(1+0.4C_{\mathrm{pV}}\Delta T_{\mathrm{W}}/h_{\mathrm{LV}})^2}. \tag{50}$$

Figure 4 shows the modified F factor, F_{M}, for the five binary systems studied in this work at two wall saturation superheats for examples. The similarity

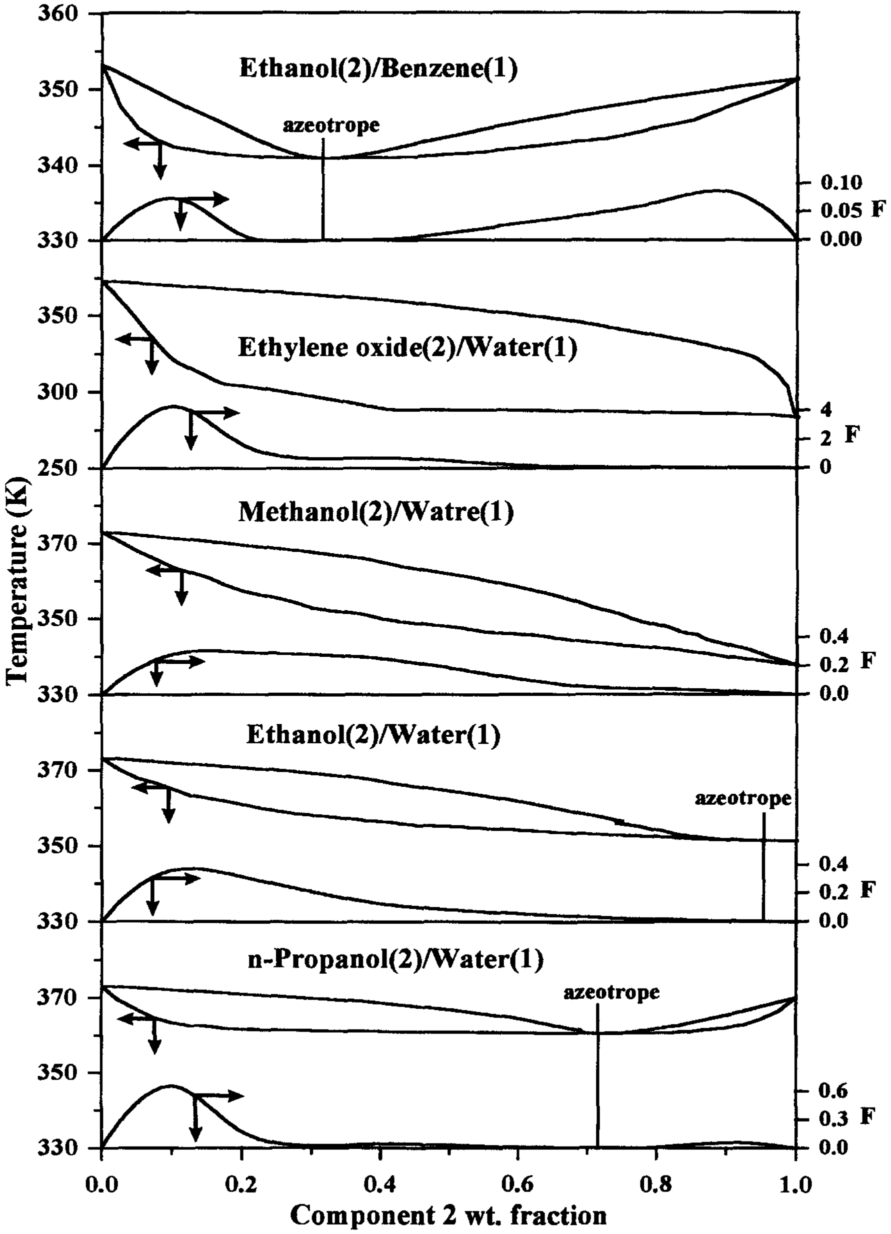

Fig. 2. Phase equilibrium diagram and F factor, equation (3), for five binary systems under atmospheric pressure.

between F_M and F is obvious as can be seen by comparing Fig. 2 with Fig. 4.

2.2.2. *Radiation parameter.* Despite its complexity, the film boiling model described above is highly idealized, and several physical effects have been ignored. In particular, the transport of heat by radiation from the heated surface to the vapor/liquid interface has not been considered. If the vapor in the film absorbs and emits radiation at infrared wavelength, a detailed treatment of the radiation interaction with the vapor may be necessary to accurately predict the film boiling heat transfer.

Fortunately, in most cases the vapor is virtually transparent to infrared radiation emitted by the wall and the interface. For thin vapor film, the radiation transport can then be modeled with reasonable accuracy as the radiation exchange between two parallel plates. If the wall and interface are modeled as infinite parallel gray surfaces with emissivity ε_W and absorptivity α_A, respectively, the heat transfer coefficient of radiation is given by

$$h_r = \frac{\sigma}{1/\varepsilon_W + 1/\alpha_A - 1} \frac{T_W^4 - T_b^4}{\Delta T_W}. \tag{51}$$

It is assumed that the radiation parameter is a func-

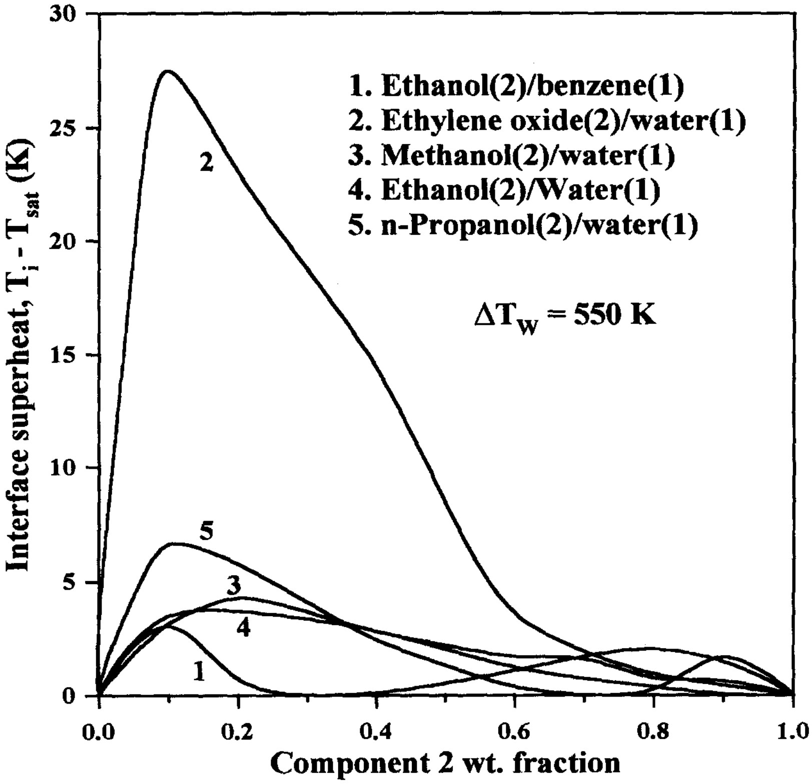

Fig. 3. Increase in vapor–liquid interface temperature due to the mass diffusion effect at $\Delta T_W = 550$ K.

tion of the ratio of heat transfer coefficient without radiation to radiation heat transfer coefficient for parallel plates. Bromley [8] performed a qualitative study on the effect of radiation and presented the simple radiation parameter equation for saturated pool film boiling of single component liquids

$$J = \frac{3}{4} + \frac{1}{4}\left(\frac{1}{1+2.62h_{co}/h_r}\right). \tag{52}$$

By assuming that equation (52) is applicable to that in film boiling of binary mixtures, one may substitute equations (49), (51), and (52) into equation (18) and obtain the approximate analytical solution of the theoretical model with mass diffusion effect and radiation effect

$$h_{mix} = 0.512\left[\frac{k_V^3 g \rho_V(\rho_b - \rho_V)H}{\mu_V \Delta T_W D}(1+F_M)\right]^{1/4} + \left[\frac{3}{4} + \frac{1}{4}\left(\frac{1}{1+2.62h_{co,mix}/h_r}\right)\right] \times \left[\frac{\sigma}{1/\varepsilon_W + 1/\alpha_A - 1}\left(\frac{T_W^4 - T_b^4}{\Delta T_W}\right)\right]. \tag{53}$$

2.3. *Physical properties*

The predictions of all relevant physical properties, including latent heat of vaporization, diffusion coefficient, and specific heat, thermal conductivity, density, and viscosity for both liquid and vapor are referred to Liu *et al.* [6].

The physical properties of binary mixtures may vary significantly from one composition to the other. Therefore, in order that the mass diffusion effect on film boiling heat transfer can be suitably assessed, the results of both rigorous solution and approximate analytical solution for a particular composition of the binary liquid mixture will be compared with that of an equivalent pure fluid (EPF), which is an ideal pure substance of exactly the same physical properties with the binary mixture under study. Just like the pure components and the azeotrope, an EPF certainly causes no mass diffusion effect on film boiling. In these situations, the pool film boiling heat transfer coefficient is evaluated in this work by the equation given by Bromley [10] for single component liquids,

$$h = 0.512\left[\frac{k_V^3 g \rho_V(\rho_b - \rho_V)H}{\mu_V \Delta T_W D}\right]^{1/4} + \left[\frac{3}{4} + \frac{1}{4}\left(\frac{1}{1+2.62h_{co}/h_r}\right)\right] \times \left[\frac{\sigma}{1/\varepsilon_W + 1/\alpha_A - 1}\left(\frac{T_W^4 - T_b^4}{\Delta T_W}\right)\right]. \tag{54}$$

It is noteworthy that equation (53) reduces to equation (54) for $F_M = 0$.

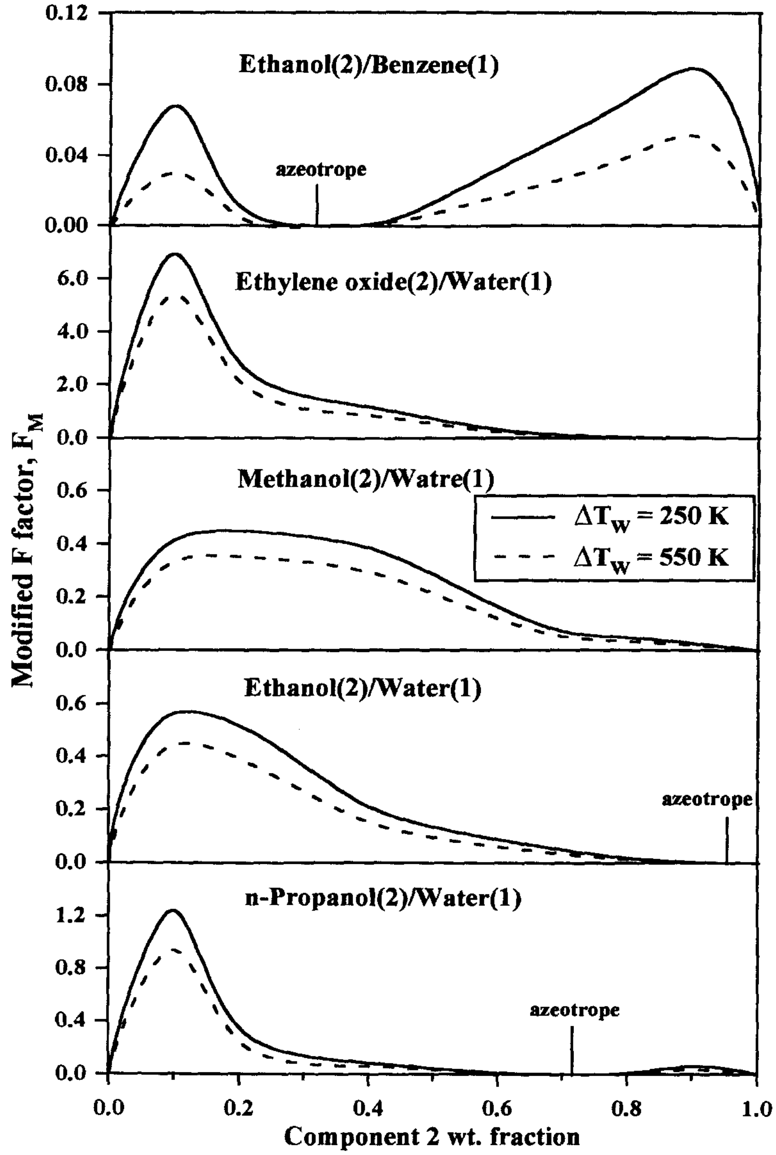

Fig. 4. Modified *F* factor, equation (50), for five binary systems at two wall superheats.

3. RESULTS AND DISCUSSION

3.1. *Comparison between the approximate analytical solution and the rigorous numerical solution*

Predictions by the proposed correlation, equation (53), and by equation (54) which depicts the result for an equivalent pure fluid are compared with the rigorous numerical solutions. Figures 5–9 show the results for ethanol/benzene, ethylene oxide/water, methanol/water, ethanol/water, and *n*-propanol/water, respectively. Composition effect of binary mixtures on pool film boiling heat transfer coefficient is shown at two wall superheats $\Delta T_W = 550$ K and 250 K for examples. Cylinder diameter $D = 12.5$ mm, radiation emissivity of heated surface $\varepsilon_W = 0.75$, and radiation absorptivity of liquid $\alpha_A = 1$ are assumed in the calculations.

The results of ethylene oxide/water binary system are also shown in Table 1 for error estimation. It is found that the heat transfer coefficients predicted by the proposed correlation agree well with the rigorous numerical solution at both wall superheats. On the other hand, equation (54) usually predicts much lower heat transfer coefficient values especially at compositions with stronger mass diffusion effect. Similar error analysis has also been made for other binary systems. Figure 10 shows the comparison between rigorous numerical results and predicted heat transfer coefficients by equation (53) and (54), respectively, based on four wall superheats ($\Delta T_W = 250$, 350, 450,

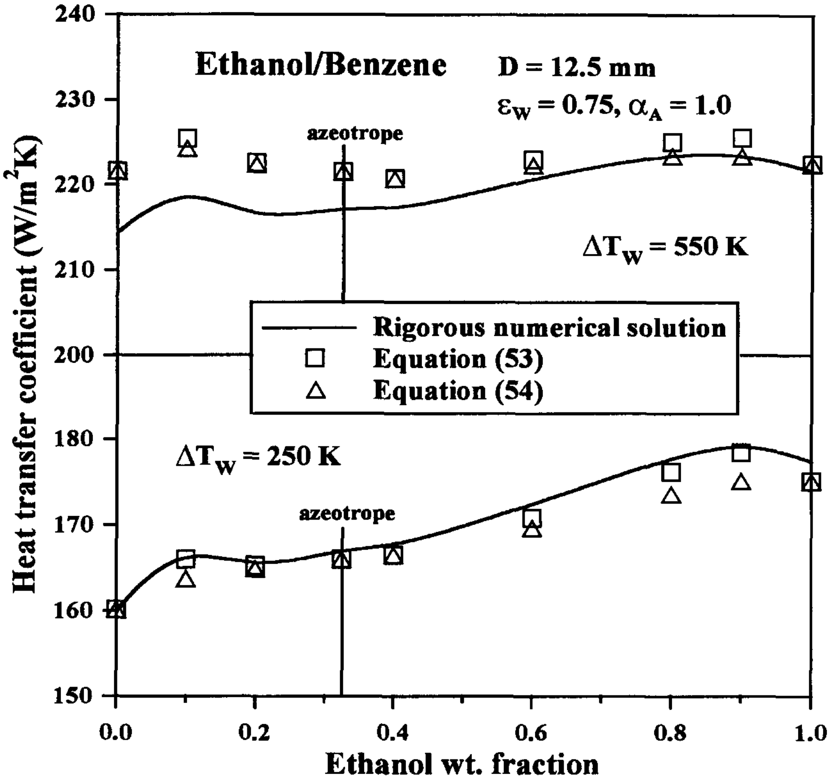

Fig. 5. Comparison between rigorous numerical results and predicted heat transfer coefficients by equation (53) and equation (54) for ethanol/benzene mixtures.

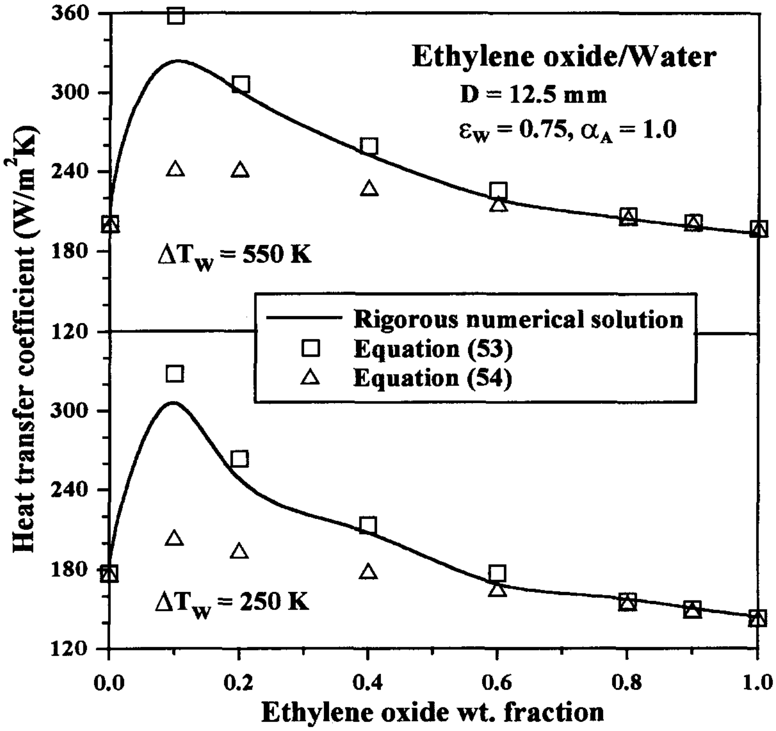

Fig. 6. Comparison between rigorous numerical results and predicted heat transfer coefficients by equation (53) and equation (54) for ethylene oxide/water mixtures.

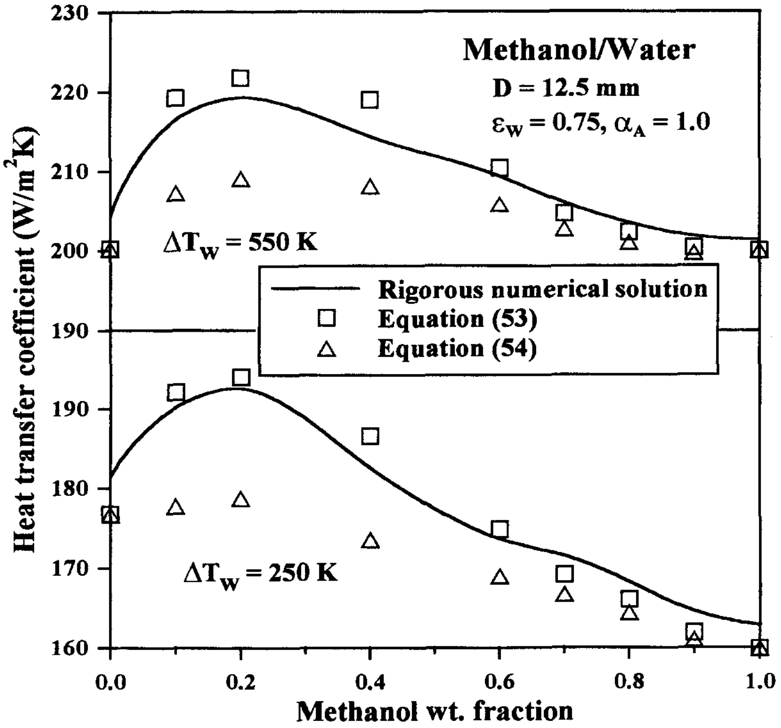

Fig. 7. Comparison between rigorous numerical results and predicted heat transfer coefficients by equation (53) and equation (54) for methanol/water mixtures.

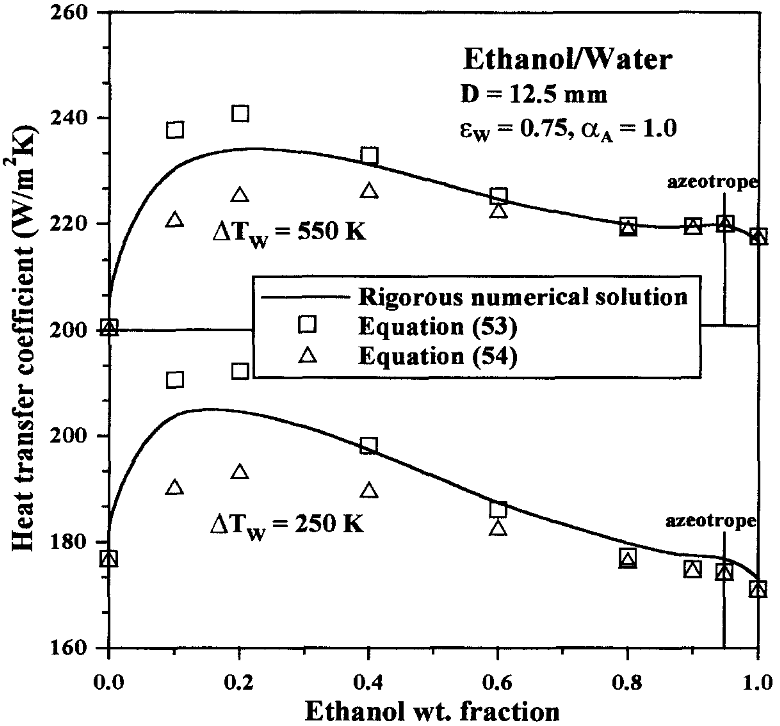

Fig. 8. Comparison between rigorous numerical results and predicted heat transfer coefficients by equation (53) and equation (54) for ethanol/water mixtures.

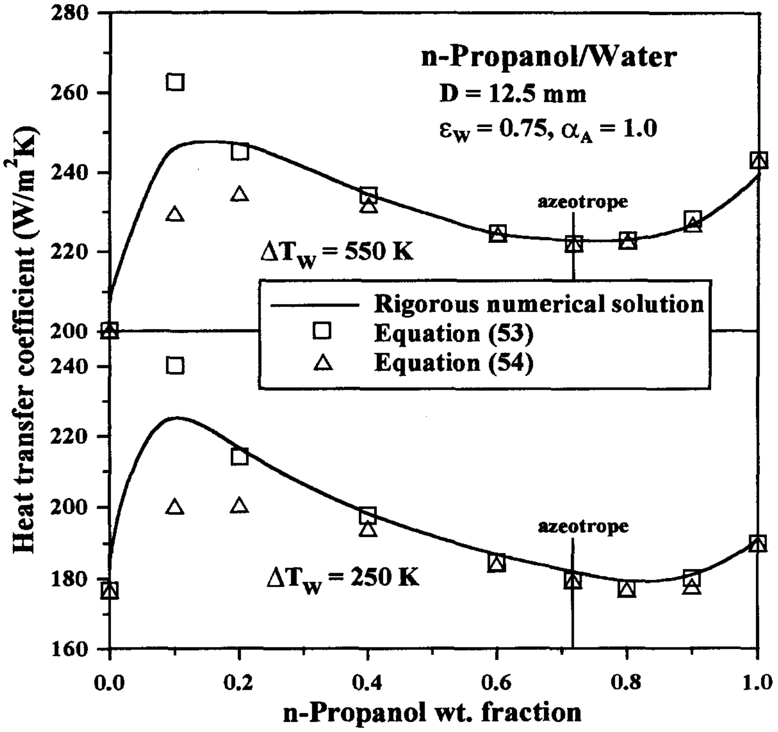

Fig. 9. Comparison between rigorous numerical results and predicted heat transfer coefficients by equation (53) and equation (54) for *n*-propanol/water mixtures.

Table 1. Comparison between rigorous numerical results and predicted heat transfer coefficient *h* ($W\ m^{-2}\ K^{-1}$) for ethylene oxide/water binary system

Weight fraction of ethylene oxide	Rigorous numerical *h*	Predicted *h* equation (53)	Error %	Predicted *h* equation (54)	Error %
(a) $\Delta T_W = 550$ K					
0.0	204.6	200.4	−2.1	200.4	−2.1
0.1	324.1	357.9	10.4	242.3	−25.2
0.2	300.6	306.2	1.9	241.9	−19.5
0.4	252.5	259.3	2.7	227.9	−9.7
0.6	218.9	225.7	3.1	216.0	−1.3
0.8	204.3	206.4	1.0	205.4	0.5
0.9	198.5	201.2	1.4	200.8	1.2
1.0	193.2	197.0	2.0	197.0	2.0
		Average error = 3.1		Average error = 7.7	
(b) $\Delta T_W = 250$ K					
0.0	181.9	176.8	−2.8	176.8	−2.8
0.1	305.9	328.1	7.3	204.1	−33.3
0.2	248.1	263.8	6.3	194.6	−21.6
0.4	207.5	213.3	2.8	178.9	−13.8
0.6	168.8	176.8	4.8	165.6	−1.9
0.8	157.6	156.0	−1.0	154.6	−1.9
0.9	150.4	149.5	−0.6	149.0	−1.0
1.0	143.8	142.8	−0.7	142.8	−0.7
		Average error = 3.3		Average error = 7.9	

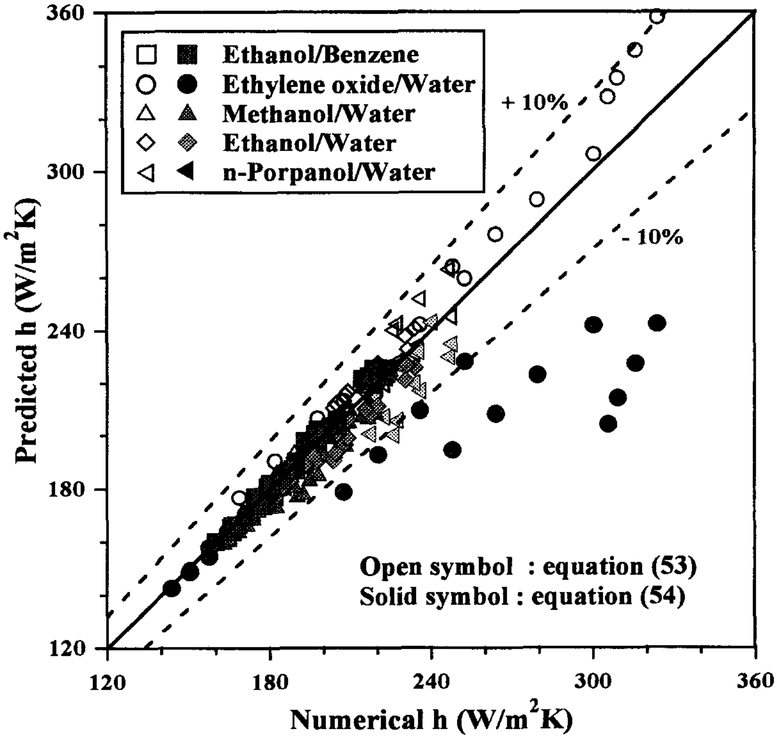

Fig. 10. Predicted heat transfer coefficients by equation (53) and equation (54) vs. numerical results.

550 K) and eight compositions (wt. fraction of component 2 = 0, 0.1, 0.2, 0.4, 0.6, 0.8, 0.9, 1) for the five binary systems.

3.2. *Extent of mass diffusion effect on film boiling heat transfer*

For film boiling of binary mixtures at sufficiently high heated wall temperature, it must be the situation that a point is reached when the heat flux is sufficiently high to reduce the concentration of the more volatile component at the interface to zero. The heat flux through the liquid phase due to the mass diffusion effect is then at its maximum and as the overall heat flux is increased, this becomes a decreasing fraction of the total. The mass diffusion effect of binary mixtures on film boiling heat transfer is thus, expected to be negligible at some high values of heated wall superheat.

Liu *et al.* [12] analyzed numerically the pool film boiling of *n*-propanol/water binary mixtures over a horizontal cylinder by the method mentioned above in Section 2.1 and proposed a criterion for the condition of negligible effect of mass diffusion on film boiling heat transfer. As a general correlation for predicting film boiling heat transfer coefficient, equation (53) does depict this essence of the mass diffusion effect of binary mixtures. As can be clearly seen in Fig. 11 for a nonazeotropic and azeotropic systems, the normalized heat transfer coefficient (i.e. the ratio of the heat transfer coefficient predicted by equation (53) to that predicted by equation (54)) decreases with the increase of wall superheat. The results reveal that the mass diffusion effect is negligible at sufficiently high values of wall superheat for a liquid mixture of particular composition. The heat transfer coefficients of pure components and the azeotrope are certainly all equal to those of the corresponding equivalent pure fluids, and consequently are represented by the horizontal line in Fig. 11 with $h/h_{\mathrm{EPF}} = 1$. Figure 12 shows the diminishing effect of mass diffusion with increasing wall superheat for liquids with 0.1 weight fraction of component two of the five binary systems. It should be noted that while equation (53) is capable of predicting the extent of the mass diffusion effect on film boiling heat transfer of binary mixtures, equation (1) is unable to do it.

4. CONCLUSIONS

As examined by five nonazeotropic and azeotropic binary systems, the proposed equation (53) is shown to predict successfully the pool film boiling heat transfer from a horizontal cylinder to saturated binary mixtures. Furthermore, this general correlation is given an advantage over previous correlations in that it predicts also the extent of the mass diffusion effect on pool film boiling heat transfer of binary mixtures.

Acknowledgement—This study was partially supported by the National Science Council of the Republic of China through grant No. NSC 85-2214-E-006-008.

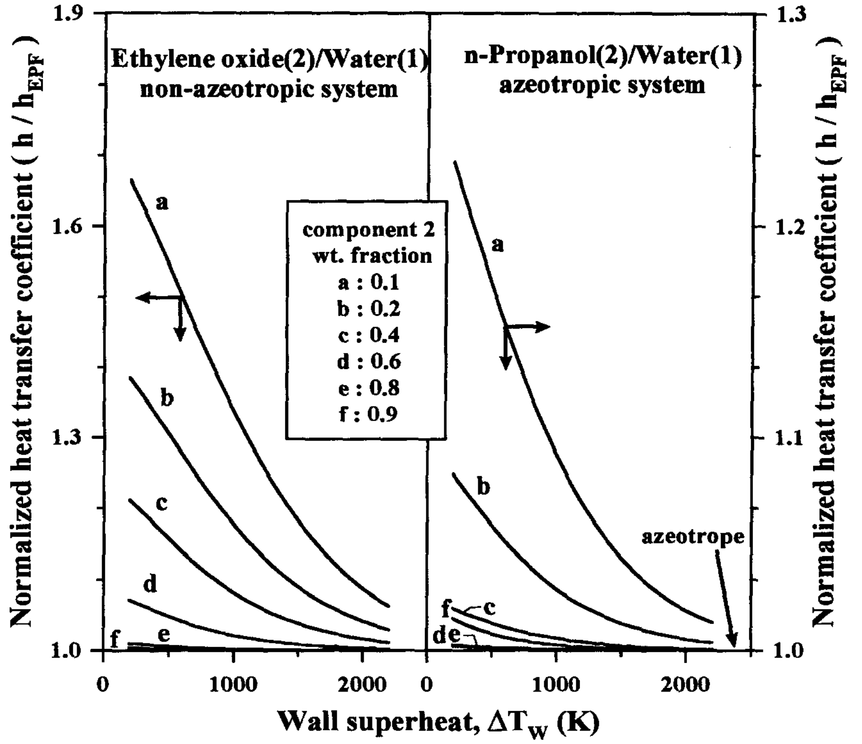

Fig. 11. Wall superheat effect on pool film boiling heat transfer of binary mixtures as depicted by equation (53).

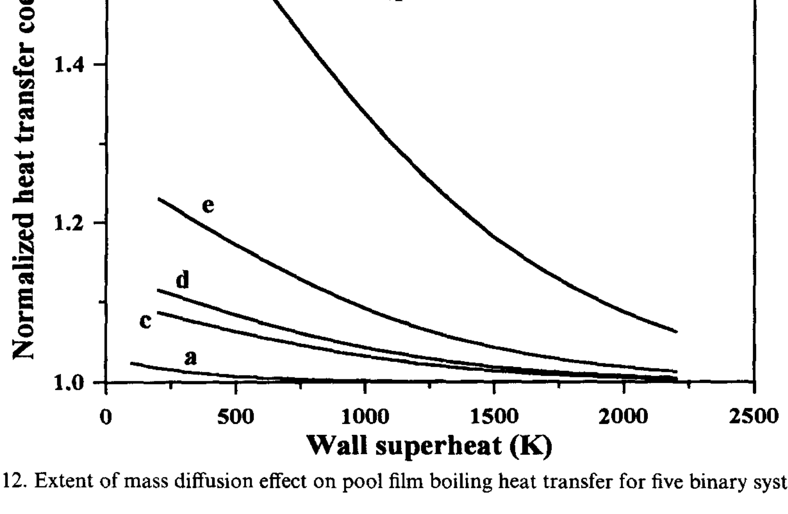

Fig. 12. Extent of mass diffusion effect on pool film boiling heat transfer for five binary systems.

REFERENCES

1. Jordan, D. P., Film and transition boiling. In *Advances in Heat Transfer*. Academic Press, 1968, **5**, 55–128.
2. Kalinin, E. K., Berlin, I. I. and Kstyuk, V. V., Film-boiling heat transfer. In *Advances in Heat Transfer*. Academic Press, 1975, **11**, 51–197.
3. Lienhard, J. H. and Witte, L. C., A historial view of the hydrodynamic theory of boiling. *Reviews in Chemical Engineering*, 1985, **3**, 189–280.
4. Sakurai, A., Film boiling heat transfer. *Proceedings of the Ninth International Heat Transfer Conference*. Jerusalem, 1990, **2**, 157–186.
5. Sarma, P. K., Prasad, P. R. K., Dharma Rao, V. and Subrahmanyam, T., Effect of thermo-physical properties on turbulent film boiling. *Wärme- und Stoffübertragung*, 1994, **30**, 83–88.
6. Liu, M. H., Yang, Y. M. and Maa, J. R., Mass diffusion effect on film boiling of saturated binary mixtures. *Numerical Heat Transfer, Part A*, 1996, **30**, 815–834.
7. Bui, T. D. and Dhir, V. K., Film boiling heat transfer on an isothermal vertical surface. *ASME Journal of Heat Transfer*, 1985, **107**, 764–771.
8. Nishio, S. and Ohtake, H., Vapor-film-unit model and heat transfer correlation for natural-convection film boiling with wave motion under subcooled conditions. *International Journal of Heat and Mass Transfer*, 1993, **36**, 2541–2552.
9. Liu, M. H., Yang, Y. M. and Maa, J. R., Prediction of film boiling heat transfer coefficients for binary mixtures. *Heat and Mass Transfer*, 1997, **32**, 261–269.
10. Bromley, L. A., Heat transfer in stable film boiling. *Chem. Engng Prog.*, 1950, **46**, 221–227.
11. Sakurai, A., Shiotsu, M. and Hata, K., A general correlation for pool film boiling heat transfer from a horizontal cylinder to subcooled liquid : part I—a theoretical pool film boiling heat transfer model including radiation contributions and its analytical solution. *ASME Journal of Heat Transfer*, 1990, **112**, 430–440.
12. Liu, M. H., Yang, Y. M. and Maa, J. R., On the extent of the mass diffusion effect on film boiling heat transfer in binary mixtures. *Numerical Heat Transfer, Part A*, 1997, **32**, 897–913.

APPENDIX

It is known that

$$\frac{Sc_L}{Pr_L} = \frac{\alpha_L}{D_L} \tag{A1}$$

and the terms $(w_{2Li}-w_{2Vi})(\Delta T_L/\Delta w_{2L})$ in equation (45) can be approximated by

$$(w_{2Li}-w_{2Vi})\left(\frac{\Delta T_L}{\Delta w_{2L}}\right) \simeq (x_2-y_2)\left(\frac{dT_L}{dx_2}\right). \tag{A2}$$

Thus, equation (45) becomes

$$F_M \simeq (x_2-y_2)\left(\frac{\alpha_L}{D_L}\right)^{1/2}\left(\frac{C_{pL}}{H}\right)\left(\frac{dT_L}{dx_2}\right)\left(\frac{Sc_L}{Pr_L}\right)^{1/6}. \tag{A3}$$

The substitution of equation (19) in equation (A3) yields

$$F_M \simeq \left[(x_2-y_2)\left(\frac{\alpha_L}{D_L}\right)^{1/2}\left(\frac{C_{pL}}{h_{LV}}\right)\left(\frac{dT_L}{dx_2}\right)\right] \times \frac{(Sc_L/Pr_L)^{1/6}}{(1+0.4Cp_V\Delta T_V/h_{LV})^2}. \tag{A4}$$

It can be easily recognized that the terms in the square brackets in equation (A4) are represented by the mass diffusion factor F. As a consequence of equations (3) and (A4), one obtains equation (46).