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Various formulas and their accuracy concerning convective heat and mass transfer in the vapor boundary layer in the case of laminar film condensation of binary vapor mixtures

TETSU FUJII and KAN'EI SHINZATO
Institute of Advanced Material Study, Kyushu University, Kasuga 816, Japan

and

JONG BOONG LEE
Department of Mechanical Engineering, Kyungnam University, Masan 630-701, Korea

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Abstract—The equations of convective mass transfer are derived from the equations of convective heat transfer by replacing Nu_c with Sh and Pr_V with Sc and also $(\chi^+/\omega)Gr$ with $(\chi/\omega)Gr$ for free-convection condensation. As for forced-convection condensation, the equations of Rose and Fujii *et al.* and the newly presented equation for mass transfer have almost the same accuracy, although their functional forms are quite different from each other. The accuracy of Rose's equation for heat transfer decreases as the effect of the enthalpy diffusion term increases. As for free-convection condensation, the newly presented equation for mass transfer is applicable in a wider range of W_R or $\dot{M}$ in comparison with the previous equation of Fujii *et al.*

1. INTRODUCTION

In THE condensation of a binary vapor mixture the Sherwood number Sh for the convective mass transfer and the Nusselt number Nu_c for the convective heat transfer in the vapor phase are functions of Reynolds number Re_V or Grashof number Gr, Schmidt number Sc or Prandtl number Pr_V, and also condensation mass flux. Fujii *et al.* [1] obtained an equation of Sh $(Re_V, Sc, W_{1Vi}/W_{1V\infty})$ from the similarity solution for forced-convection condensation of an air–stream mixture on a flat surface, where W_{1Vi} and $W_{1V\infty}$ are the mass concentrations of air at the vapor–liquid interface and in the main stream, respectively. Further, they derived an equation of Nu_c $(Re_V, Pr_V, \dot{M}_{FV})$ by replacing Sh with Nu_c and Sc with Pr_V and by transforming $W_{1Vi}/W_{1V\infty}$ to the dimensionless mass flux $\dot{M}_{FV}$ using one of the compatibility conditions at the vapor–liquid interface. The Nu_c equation correlates well the data for the heat transfer of the similarity solution. Rose [2] presented an equation of $Nu_{cx}\,Re_{Vx}^{-1/2}$ as the function of Pr_V and a suction parameter in the case of single phase, simultaneous heat and mass transfer. Further, he [3] clarified, using the similarity solutions by Koh [4], Fujii *et al.* [1], and Sparrow *et al.* [5], that the equation is applicable to the convective mass transfer in the case of forced-convection condensation of a vapor with a non-condensing gas, when Nu_c and Pr_V are replaced with Sh and Sc, respectively.

In the above-mentioned analyses, however, the enthalpy diffusion term in the energy equation of vapor phase is neglected. Consequently the effect of the term upon the heat transfer should be clarified. It will also be significant to confirm the possibility of analogical transformation between Nu_c and Sh in free-convection condensation. In this paper, these two items are discussed. Prior to the discussion, the convective mass transfer coefficient and corresponding Sherwood number are closely defined.

2. RELATIONS AMONG MASS TRANSFER COEFFICIENT, SHERWOOD NUMBER, AND CONDENSATION MASS FLUX

In the case of the condensation of a binary vapor mixture, the mass transfer coefficient β_x between the vapor–liquid interface and the bulk vapor mixture and the corresponding Sherwood number Sh_x are defined, respectively, by

$$-\left(\rho_V D\frac{\partial W_{1V}}{\partial y}\right)_i = \beta_x(W_{1Vi}-W_{1V\infty}) \qquad (1)$$

$$Sh_x = \frac{\beta_x x}{\rho_V D} \qquad (2)$$

where ρ_V is the density of the vapor mixture, D the diffusivity between components 1 and 2, W_{1V} the mass concentration of volatile component 1, y the normal distance from the cooling surface, x the distance measured along the cooling surface from its leading edge.

NOMENCLATURE

$C_F(Pr_V)$	function of Pr_V, equation (22)
$C_F(Sc)$	function of Sc, equation (22)
$C_G(Pr_V)$	function of Pr_V, equation (36)
$C_G(Sc)$	function of Sc, equation (36)
c_p	isobaric specific heat
c_{p12}	dimensionless isobaric specific heat difference, equation (27)
D	diffusivity between components 1 and 2 in a binary vapor mixture
Gr	Grashof number, equation (42)
g	gravitational acceleration
M	molecular weight
$\dot M_{FV}$	dimensionless condensate mass flux defined by using physical properties of vapor mixture for forced-convection condensation, equation (21)
$\dot M_{GV}$	dimensionless condensate mass flux defined by using physical properties of vapor mixture for free-convection condensation, equation (41)
$\dot m$	condensation mass flux [mass condensed per unit time per unit area]
Nu_c	Nusselt number corresponding to α_c, equations (17), (33) and (47)
Pr	Prandtl number, $\mu c_p/\lambda$
p	static pressure
q_c	heat flux in the vapor side at the vapor–liquid interface
q_w	heat flux at the cooling surface
R	$\rho\mu$ ratio, $(\rho_L\mu_L/\rho_V\mu_V)^{1/2}$
Re_V	Reynolds number, equation (16)
Sc	Schmidt number, ν_V/D
Sh	Sherwood number, equations (2), (6), (15), (32), (45) and (46)
T	temperature
$U_{V\infty}$	main stream vapor velocity in the x direction
W	mass concentration (mass fraction)
W_R	$(W_{1Vi}-W_{1L})/(W_{1V\infty}-W_{1L})$, equation (25)
x	distance measured along the cooling surface from the leading edge
y	normal distance from the cooling surface.

Greek symbols

β	mass transfer coefficient, equations (1), (4), (14) and (31)
Δh_V	latent heat of condensation
$\Delta T_{V\infty}$	degree of superheat of bulk vapor, $T_{V\infty}-T_{s\infty}$
δ	condensate film thickness
η_{FV}	similarity variable for the vapor boundary layer in forced-convection condensation, equation (13)
η_{GV}	similarity variable for the vapor boundary layer in free-convection condensation, equation (30)
Θ	dimensionless temperature $(T_{V\infty}-T_V)/(T_{V\infty}-T_i)$, equation (18)
κ	thermal diffusivity
λ	thermal conductivity
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density
Φ	normalized mass concentration of vapor, equation (12)
χ	equation (37)
χ^+	equation (38)
ω	equation (43)
ω_T	equation (40)
ω_w	equation (39).

Superscript

	differential derivative with respect to η_{FV} or η_{GV}.

Subscripts

1, 2	volatile and less volatile components of binary vapor mixture, respectively
F	forced-convection condensation
G	free-convection condensation
i	vapor–liquid interface
L	condensate
s	saturated
sim	similarity solution
V	vapor
w	cooling surface
x	local values at x
∞	bulk, at $y = \infty$.

The subscripts V, i, and ∞ denote the values in the vapor, vapor–liquid interface, and bulk vapor, respectively.

The compatibility condition for the mass concentration at the vapor–liquid interface, based on the boundary layer assumption, is expressed as

$$\dot m_{1x} = W_{1Vi}\dot m_x + \rho_V D\left(\frac{\partial W_{1V}}{\partial y}\right)_i \qquad (3)$$

where $\dot m_{1x}$ is the condensation mass flux of component 1, $\dot m_x$ the total condensation mass flux. From equations (1) and (3), β_x is derived as

$$\beta_x = \frac{W_{1Vi}\dot m_x - \dot m_{1x}}{W_{1Vi}-W_{1V\infty}}. \qquad (4)$$

When the condensate is miscible, the mass concentration W_{1L} of component 1 in the condensate is expressed as

$$W_{1L} = \frac{\dot{m}_{1x}}{\dot{m}_x}. \tag{5}$$

Substituting $\dot{m}_x$ in equation (5) into equation (4), and substituting it into equation (2), we obtain

$$Sh_x = \frac{\dot{m}_x x(W_{1Vi} - W_{1L})}{\rho_V D(W_{1Vi} - W_{1V\infty})}. \tag{6}$$

For a given value of T_i, the values of W_{1Vi} and W_{1L} are obtained from the phase equilibrium relation, and then the value of $\dot{m}_x$ can be calculated by using a Sh_x equation and equation (6). The value of T_i is calculated by using a heat transfer equation for the condensate film, which is a function of $\dot{m}_x$. Therefore, the solution of the simultaneous equations of mass transfer for the vapor phase and heat transfer for the condensate film provides the thermal state at the vapor–liquid interface and the condensation mass flux.

In the case where the component 1 is a non-condensing gas, it is taken that $\dot{m}_{1x} = 0$ ($\dot{m}_{2x} = \dot{m}_x$), and $W_{1L} = 0$ in the above equations. In this case, other definitions of the mass transfer coefficient β_x^* and the Sherwood number Sh_x^* are used in refs. [1, 3] as

$$\beta_x^* = \frac{\dot{m}_x}{(W_{1Vi} - W_{1V\infty})} \tag{7}$$

$$Sh_x^* = \frac{\beta_x^* x}{\rho_V D} = \frac{\dot{m}_x x}{\rho_V D(W_{1Vi} - W_{1V\infty})}. \tag{8}$$

By comparing equation (4) with equation (7) and equation (6) with equation (8), the following relations are obtained:

$$\beta_x = W_{1Vi}\beta_x^* \tag{9}$$

$$Sh_x = W_{1Vi}\, Sh_x^*. \tag{10}$$

3. AN ANALOGICAL TRANSFORMATION BETWEEN THE EQUATIONS OF MASS TRANSFER AND HEAT TRANSFER, AND THEIR ACCURACY

3.1. *Forced-convection condensation on a flat surface*

According to the similarity transformation [6], the gradient of mass concentration at the vapor–liquid interface is given as

$$\left(\frac{\partial W_{1V}}{\partial y}\right)_i = (W_{1Vi} - W_{1V\infty})\left(\frac{U_{V\infty}}{\nu_V x}\right)^{1/2} \Phi'_{Fi} \tag{11}$$

where $U_{V\infty}$ is the vapor mixture velocity in the main stream, ν_V the kinematic viscosity of the vapor mixture, and Φ_F the normalized mass concentration of component 1, which is defined by

$$\Phi_F = \frac{W_{1V} - W_{1V\infty}}{W_{1Vi} - W_{1V\infty}} \tag{12}$$

and the prime denotes the differential derivative with respect to the following similarity variable:

$$\eta_{FV} = (y - \delta)\left(\frac{U_{V\infty}}{\nu_V x}\right)^{1/2} \tag{13}$$

where δ is the condensate film thickness.

Eliminating $(\partial W_{1V}/\partial y)_i$ from equations (11) and (1), we obtain

$$\beta_x = \rho_V D\left(\frac{U_{V\infty}}{\nu_V x}\right)^{1/2}(-\Phi'_F). \tag{14}$$

Substituting equation (14) into equation (2), we obtain

$$Sh_x = -\Phi'_F\, Re_{Vx}^{1/2} \tag{15}$$

where

$$Re_{Vx} = \frac{U_{V\infty} x}{\nu_V}. \tag{16}$$

On the other hand, the Nusselt number Nu_{cx} for the convective heat transfer in the vapor side is given as [6]

$$Nu_{cx} = \frac{\alpha_{cx} x}{\lambda_V} = -\Theta'_{FVi}\, Re_{Vx}^{1/2} \tag{17}$$

where Θ_{FVi} is the dimensionless temperature defined by

$$\Theta_{FVi} = \frac{T_{V\infty} - T_V}{T_{V\infty} - T_i}. \tag{18}$$

The functional form of equations (15) and (17) is the same.

The formulas of Φ'_{Fi} and Θ'_{FVi} for a vapor with non-condensing gas which were proposed by Rose [3], are expressed as

$$-\Phi'_{Fi} = \frac{C_F(Sc)}{1 + 0.941\dot{M}_{FV}^{1.14}\, Sc^{0.93}} + \dot{M}_{FV}\, Sc \tag{19}$$

$$-\Theta'_{FVi} = \frac{C_F(Pr_V)}{1 + 0.941\dot{M}_{FV}^{1.14}\, Pr_V^{0.93}} + \dot{M}_{FV}\, Pr_V \tag{20}$$

where

$$\dot{M}_{FV} = \frac{\dot{m}_x x}{\mu_V\, Re_{Vx}^{1/2}} \tag{21}$$

$$C_F(\zeta) = \zeta^{1/2}(27.8 + 75.9\zeta^{0.306} + 657\zeta)^{-1/6}$$

$$\zeta = Sc \quad \text{or} \quad Pr_V. \tag{22}$$

The functional form of equations (19) and (20) is also the same. On the other hand, the present authors [6, 7] proposed the following equations from the numerical solutions for mixtures of ethanol–water, CFC114–CFC11 and a mixture of water, ethanol, CFC114 and HCFC22 with air

$$-\Phi'_{Fi} = C_F(Sc)\left(\frac{2.5}{1.5 + W_R}\right)^{m} W_R \tag{23}$$

$$-\Theta'_{FVi} = C_F(Pr_V)(1 + 2.6Pr_V^{0.66}\, \dot{M}_{FV}^{1.05} \times \{1 - \tfrac{2}{3}c_{p12}(W_{1Vi} - W_{1L})\}) \tag{24}$$

where

$$W_R = \frac{W_{1Vi} - W_{1L}}{W_{1V\infty} - W_{1L}} \tag{25}$$

$$m = 0.5 + 0.05Sc - 0.2R^{-1/2} \tag{26}$$

$$c_{p12} = \frac{c_{p1V} - c_{p2V}}{c_{p1V}W_{1V} + c_{p2V}W_{2V}} = \frac{c_{p1V} - c_{p2V}}{c_{pV}} \tag{27}$$

and R is the $\rho\mu$ ratio and c_p the isobaric specific heat. When the term $(2/3)c_{p12}(W_{1Vi} - W_{1L})$ in equation (24) (the effect of enthalpy diffusion) is neglected, an analogy between Φ'_{Fi} and Θ'_{FVi} is valid and Φ'_{Fi} is expressed as

$$-\Phi'_{Fi} = C_F(Sc)(1 + 2.6Sc^{0.66}\dot{M}_{FV}^{1.05}). \tag{28}$$

Table 1 shows some examples of the comparison of the numerical solutions of Φ'_{Fi} with equations (19), (23) and (28), and Θ'_{FVi} with equations (20) and (24). As for Φ'_{Fi}, the errors of equations (19), (23) and (28) are less than 1, 2, and 2.5%, respectively. As for Θ'_{FVi}, the error of equation (24) is less than 2%, while the maximum error of equation (20) becomes about 16% in some cases of the air–stream mixture, because equation (20) was derived from the numerical solution of the basic equations in which the enthalpy diffusion term is neglected. However, the effect of this error upon the heat flux at the cooling surface is small, because the values of q_{cx} are much smaller than those of q_{wx}. On the other hand, when the values of q_{cx} and q_{wx} are comparable and the values of $\dot{M}_{FV}$ are small, the effect of enthalpy diffusion term upon the value of Φ'_{Fi} becomes small.

3.2. *Free-convection condensation on a vertical flat surface*

According to the similarity transformation [6], the gradient of mass concentration at the vapor–liquid interface is given as

$$\left(\frac{\partial W_{1V}}{\partial y}\right)_i = (W_{1Vi} - W_{1V\infty})\left(\frac{g}{4\nu_V^2 x}\right)^{1/4}\Phi'_{Gi} \tag{29}$$

where g is the gravitational acceleration, Φ'_G the differential derivative of normalized mass concentration with respect to the following similarity variable:

$$\eta_{GV} = (y - \delta)\left(\frac{g}{4\nu_V^2 x}\right)^{1/4}. \tag{30}$$

Similarly to the case of forced-convection condensation, the following equations are obtained from equations (29), (1) and (2)

$$\beta_x = \rho_V D\left(\frac{g}{4\nu_V^2 x}\right)^{1/4}(-\Phi'_{Gi}) \tag{31}$$

$$Sh_x = \left(\frac{gx^3}{4\nu_V^2}\right)^{1/4}(-\Phi'_{Gi}). \tag{32}$$

On the other hand, the Nusselt number Nu_{cx} for the convective heat transfer coefficient of vapor phase is given as [6]

$$Nu_{cx} = \left(\frac{gx^3}{4\nu_V^2}\right)^{1/4}(-\Theta'_{GVi}). \tag{33}$$

The functional form of equations (32) and (33) is the same.

Fujii [6] proposed the following formulas from the similarity solution for the mixtures of ethanol–water and air–water:

$$-\Phi'_{Gi} = \sqrt{2}C_G(Sc)(\chi\, Sc)^{1/4}\left(\frac{2}{1 + W_R}\right)^{0.5} W_R^{0.8},$$
$$1 \leqslant W_R < 100 \tag{34}$$

$$-\Theta'_{GVi} = \sqrt{2}C_G(Pr_V)(\chi^+\, Pr_V)^{1/4}$$
$$\times [1 + 1.13Pr_V^{0.66}(\dot{M}_{GV})^{1.17}\{1 - 0.85c_{p12}$$
$$\times (W_{1Vi} - W_{1L})\}], \quad \dot{M}_{GV} \gtrsim 1 \tag{35}$$

where

$$C_G(\zeta) = \frac{3}{4}\left\{\frac{\zeta}{2.4 + 4.9\sqrt{\zeta} + 5\zeta}\right\}^{1/4}, \quad \zeta = Sc \quad \text{or} \quad Pr_V \tag{36}$$

$$\chi = \omega_w + \omega_T\left(\frac{Sc}{Pr_V}\right)^{1/2} - \omega_w\omega_T \tag{37}$$

$$\chi^+ = \omega_w\left(\frac{Pr_V}{Sc}\right)^{1/2} + \omega_T - \omega_w\omega_T \tag{38}$$

$$\omega_w = \frac{(M_2 - M_2)(W_{1Vi} - W_{1V\infty})}{M_1 - (M_1 - M_2)M_{1V\infty}} \tag{39}$$

$$\omega_T = \frac{(T_{V\infty} - T_i)}{T_{V\infty}} \tag{40}$$

$$\dot{M}_{GV} = \frac{\dot{m}_x x}{\mu_V\left(\frac{Gr_x}{4}\right)^{1/4}} \tag{41}$$

$$Gr_x = \frac{x^3 g\omega}{\nu_V^2} \tag{42}$$

$$\omega = \omega_w + \omega_T - \omega_w\omega_T \tag{43}$$

and M_1 and M_2 are the molecular weights of volatile and less volatile components, respectively. When the effect of the enthalpy diffusion term in equation (35) is neglected, similarly to the case of forced-convection condensation, Φ'_{Gi} can be expressed from the analogy between heat and mass transfer as

$$-\Phi'_{Gi} = \sqrt{2}C_G(Sc)(\chi\, Sc)^{1/4}\{1 + 1.13Sc^{0.66}$$
$$\times (\dot{M}_{GV})^{1.17}\}. \tag{44}$$

In Fig. 1, the similarity solution is plotted in the coordinate of

$$[\{-\Phi'_{Gi}/\sqrt{2}C_G(Sc)(\chi\, Sc)^{1/4}\} - 1]Sc^{-0.66} \quad \text{vs} \quad \dot{M}_{GV},$$

and the solid line expresses equation (44). The agreement between them is good. Table 2 shows some

Table 1. Comparisons of the similarity solution Φ'_{Fi} with equations (19), (23) and (28) and Θ'_{FVi} with equations (20) and (24) in the case of forced-convection condensation

No.	p (MPa)	$T_{s,\infty}$ (°C)	$W_{1V,\infty}$	η_{FLi}	$\Delta T_{V,\infty}$ (°C)	T_i (°C)	T_w (°C)	W_{1Vi}	W_{1L}	R	Sc	Pr_V	$-c_{p12}\Delta W$	$1-\frac{q_{cx}}{q_{wx}}$	Similarity solutions			$\frac{\Phi'_{19}}{\Phi'_{\mathrm{sim}}}-1$	$\frac{\Phi'_{23}}{\Phi'_{\mathrm{sim}}}-1$	$\frac{\Phi'_{28}}{\Phi'_{\mathrm{sim}}}-1$	$\frac{\Theta'_{20}}{\Theta'_{\mathrm{sim}}}-1$	$\frac{\Theta'_{24}}{\Theta'_{\mathrm{sim}}}-1$
															$-\Phi'_{\mathrm{Fi}}$	$-\Theta'_{\mathrm{FVi}}$	M_{FV}					
1-1	0.1	98.0	0.1451	1.50	0	96.37	93.81	0.2615	0.0306	178.0	0.764	0.934	0.0233	0.997	0.4996	0.5678	0.3295	0.00	0.02	0.01	−0.00	0.02
1-2	0.1	98.0	0.1451	1.50	0	96.37	93.81	0.2615	0.0306	178.0	0.764	0.934	0	0.997	0.4996	0.5640	0.3295	0.00	0.02	0.01	0.00	0.02
1-3	0.1	98.0	0.1451	1.50	100	96.37	93.39	0.2615	0.0306	178.4	0.764	0.934	0.0233	0.857	0.4996	0.5679	0.3296	0.00	0.02	0.01	−0.00	0.02
1-4	0.1	98.0	0.1451	1.97	0	90.15	50.64	0.5514	0.1156	241.9	0.683	0.907	0.0441	0.993	1.6403	2.1854	2.2399	−0.00	−0.02	0.01	−0.02	0.00
1-5	0.1	98.0	0.1451	1.97	0	90.15	50.66	0.5513	0.1156	241.9	0.683	0.907	0	0.993	1.6402	2.1341	2.2396	−0.00	−0.02	0.01	−0.00	0.00
1-6	0.1	98.0	0.1451	1.97	100	90.14	44.01	0.5520	0.1160	254.3	0.683	0.907	0.0442	0.906	1.6510	2.2006	2.2570	−0.00	−0.02	0.01	−0.02	0.00
1-7	0.1	94.0	0.3946	1.00	0	92.32	91.68	0.4704	0.0804	171.0	0.635	0.892	0.0395	0.994	0.3329	0.3894	0.1018	0.00	0.00	−0.01	0.00	−0.00
1-8	0.1	94.0	0.3946	1.80	0	84.73	68.50	0.7006	0.2650	220.9	0.568	0.874	0.0442	0.988	0.6416	0.9042	0.7932	−0.00	0.01	0.01	−0.02	0.02
1-9	0.1	94.0	0.3946	1.80	0	84.73	68.51	0.7006	0.2650	220.9	0.568	0.874	0	0.989	0.6416	0.8864	0.7932	−0.00	0.01	0.01	−0.00	0.02
1-10	0.1	94.0	0.3946	1.80	100	84.73	66.08	0.7006	0.2650	225.3	0.568	0.874	0.0442	0.878	0.6417	0.9043	0.7933	−0.00	0.01	0.01	−0.02	0.02
1-11	0.1	94.0	0.3946	1.91	0	83.52	43.07	0.7278	0.3277	277.5	0.560	0.872	0.0405	0.988	0.9157	1.3621	1.3610	−0.00	0.00	0.02	−0.02	0.01
1-12	0.1	94.0	0.3946	1.91	0	83.52	43.09	0.7278	0.3277	277.5	0.560	0.872	0	0.988	0.9157	1.3334	1.3610	−0.00	0.00	0.02	−0.00	0.01
1-13	0.1	94.0	0.3946	1.91	100	83.51	34.41	0.7279	0.3280	300.8	0.560	0.872	0.0405	0.988	0.9175	1.3651	1.3648	−0.00	−0.00	0.02	−0.02	0.01
2-1	0.5	61.0	0.8178	1.60	0	59.64	46.39	0.8599	0.7671	31.3	0.433	0.754	−0.0184	0.986	0.3949	0.5497	0.4137	−0.01	−0.01	−0.01	−0.00	0.00
2-2	0.5	61.0	0.8178	1.90	0	59.00	16.97	0.8785	0.7949	34.9	0.431	0.754	−0.0231	0.993	0.5932	1.5130	1.6746	−0.01	−0.01	0.01	0.01	0.00
2-3	0.5	58.0	0.9059	1.90	0	56.76	14.52	0.9398	0.8927	34.4	0.416	0.760	−0.0320	0.985	0.9446	1.4393	1.6777	−0.01	−0.01	0.01	0.01	0.00
2-4	0.7	90.0	0.1809	2.00	0	88.49	9.65	0.2599	0.1667	32.3	0.483	0.832	−0.0165	0.987	0.6330	0.9728	1.0653	−0.01	−0.01	0.00	−0.00	0.01
2-5	0.7	85.0	0.4353	2.00	0	82.15	1.23	0.5562	0.4134	32.5	0.477	0.790	−0.0091	0.991	0.6153	0.9801	1.0625	−0.01	−0.01	0.00	−0.00	0.01
3-1	0.1	98.5	0.0625	1.80	0	95.68	88.01	0.1983	0	194.7	0.521	0.924	0.1056	0.997	0.6025	0.9717	0.7916	−0.00	0.01	0.01	−0.05	0.02
3-2	0.1	98.5	0.0625	1.90	0	92.56	78.51	0.3222	0	198.3	0.525	0.900	0.1769	0.994	0.8215	1.4135	1.2613	−0.00	0.00	0.02	−0.09	0.01
3-3	0.1	96.0	0.1842	1.00	0	95.10	94.55	0.2232	0	183.9	0.526	0.896	0.1233	0.997	0.3065	0.3943	0.1019	0.00	−0.00	−0.01	−0.01	−0.00
3-4	0.1	90.0	0.4068	1.00	0	86.87	86.21	0.4947	0	171.7	0.542	0.807	0.3113	0.990	0.3105	0.3842	0.1018	0.00	−0.00	−0.01	−0.03	−0.00
3-5	0.1	90.0	0.4068	1.00	0	86.87	86.21	0.4947	0	171.7	0.542	0.807	0	0.991	0.3105	0.3704	0.1018	0.00	−0.00	−0.01	0.01	−0.00
3-6	0.1	90.0	0.4068	1.60	0	63.91	57.66	0.8372	0	188.8	0.554	0.755	0.5803	0.970	0.4583	0.6619	0.4251	0.00	0.01	0.01	−0.16	0.01
3-7	0.1	90.0	0.4068	1.60	0	63.91	57.69	0.8372	0	188.8	0.554	0.755	0	0.974	0.4583	0.5552	0.4251	0.00	0.01	0.01	0.00	0.01
3-8	0.1	90.0	0.4068	1.60	10	63.91	57.59	0.8372	0	188.9	0.554	0.755	0.5803	0.959	0.4583	0.6619	0.4251	0.00	0.01	0.01	−0.16	0.01
3-9	0.1	90.0	0.4068	1.60	10	63.91	57.63	0.8372	0	188.8	0.554	0.755	0	0.965	0.4583	0.5552	0.4251	0.00	0.01	0.01	0.00	0.01
3-10	0.1	30.0	0.9732	0.36	0	1.373	1.228	0.9958	0	281.9	0.596	0.707	0.8398	0.681	0.2814	0.3028	0.0107	−0.00	−0.00	−0.01	−0.01	−0.01
3-11	0.1	30.0	0.9732	0.36	50	1.363	1.138	0.9958	0	281.6	0.596	0.707	0.8398	0.438	0.2814	0.3028	0.0107	−0.00	−0.00	−0.01	−0.01	−0.01
4-1	0.05	60.0	0.0409	1.80	0	57.32	34.13	0.1144	0	273.5	0.415	0.853	0.0479	0.994	0.5146	0.8914	0.7957	−0.00	−0.00	0.01	−0.02	0.02
4-2	0.05	50.0	0.3050	1.20	0	45.02	41.67	0.4230	0	262.4	0.606	0.771	0.1946	0.975	0.3556	0.4128	0.1637	0.00	0.00	−0.00	−0.03	0.00
5-1	0.2	18.0	0.0297	1.60	0	15.56	6.64	0.0460	0	65.6	0.237	0.718	0	0.977	0.2810	0.5371	0.4207	−0.01	−0.02	−0.02	−0.00	0.01
5-2	0.5	50.0	0.0201	1.40	0	48.85	41.77	0.0261	0	31.7	0.206	0.739	−0.1430	0.829	0.4127	0.3999	0.2583	−0.00	0.01	−0.00	0.03	−0.00
5-3	0.5	20.0	0.2295	1.40	0	5.49	−1.55	0.3802	0	57.9	0.633	0.629	0	0.825	0.4127	0.4114	0.2583	−0.00	0.01	−0.00	−0.00	−0.00
5-4	0.5	20.0	0.2295	1.40	0	5.49	−1.58	0.3802	0	57.9	0.633	0.629	−0.0079	0.983	0.2331	0.4492	0.2566	−0.01	−0.02	−0.03	−0.00	−0.00
6-1	0.8	12.0	0.0348	1.30	0	11.06	6.71	0.0448	0	24.9	0.288	0.909	−0.0116	0.990	0.2626	0.4672	0.2038	−0.01	−0.02	−0.02	−0.00	−0.00
6-2	0.8	12.0	0.0348	1.50	0	10.45	2.48	0.0511	0	25.5	0.290	0.903	−0.0134	0.988	0.2926	0.5516	0.3224	−0.01	−0.02	−0.02	−0.00	0.00

1, Ethanol–water; 2, CFC114–CFC11; 3, air–water; 4, air–ethanol; 5, air–CFC114; 6, air–HCFC22. $\Delta T_{V,\infty} = T_{V,\infty} - T_{s,\infty}$. $\Delta W = W_{1Vi} - W_{1L}$. Φ'_{19}, Φ'_{23}, Φ'_{28}, calculated by equations (19), (23) and (28), respectively. Θ'_{20}, Θ'_{24}, calculated by equations (20) and (24), respectively.

Table 2. Comparisons of the similarity solution Φ'_{Gi} with equations (44) and (34) and Θ'_{GVi} with equation (35) in the case of free-convection condensation

														Similarity solutions				
No.	p (MPa)	$T_{s\infty}$ (°C)	$W_{1V\infty}$	η_{GLi}	$\Delta T_{V\infty}$ (°C)	T_i (°C)	T_w (°C)	W_{1Vi}	W_{1L}	R	Sc	Pr_V	$-c_{p12}\Delta W$	$-\Phi'_{Gi}$	$-\Theta'_{GVi}$	M_{GV}	$\frac{\Phi'_{44}}{\Phi'_{sim}}-1$	$\frac{\Phi'_{34}}{\Phi'_{sim}}-1$	$\frac{\Theta'_{35}}{\Theta'_{sim}}-1$
1-1	0.1	98.0	0.1451	0.15	0	94.26	93.76	0.3818	0.0545	176.1	0.731	0.922	0.03306	0.6060	0.7427	0.9390	−0.01	−0.02	−0.02
1-2	0.1	98.0	0.1451	0.15	0	94.26	93.76	0.3818	0.0545	176.1	0.731	0.922	0	0.6060	0.7327	0.9390	−0.01	−0.02	−0.02
1-4	0.1	98.0	0.1451	0.30	0	88.76	75.04	0.5957	0.1432	210.3	0.670	0.902	0.04570	3.7992	5.2548	7.5150	−0.01	−0.30	0.02
1-5	0.1	98.0	0.1451	0.30	0	88.76	75.05	0.5957	0.1432	210.3	0.670	0.902	0	3.7991	5.1189	7.5148	−0.01	−0.30	0.01
1-6	0.1	98.0	0.1451	0.30	100	88.76	73.30	0.5957	0.1431	213.3	0.670	0.903	0.04571	3.8561	5.3333	6.9447	−0.03	−0.26	0.00
1-7	0.1	94.0	0.3946	0.15	0	85.12	84.14	0.6916	0.2487	194.9	0.571	0.875	0.04473	0.5670	0.8111	0.9361	−0.00	−0.01	−0.01
1-8	0.1	94.0	0.3946	0.25	0	82.63	71.11	0.7472	0.3907	221.2	0.555	0.872	0.03601	1.9384	3.1056	4.6516	−0.02	−0.05	0.01
1-9	0.1	88.5	0.6034	0.20	0	80.77	75.33	0.7910	0.5878	204.9	0.480	0.859	0.02052	0.8572	1.5073	2.4697	0.01	−0.01	0.01
1-10	0.1	88.5	0.6034	0.20	100	80.80	74.54	0.7902	0.5845	206.3	0.481	0.859	0.02078	0.8812	1.5409	2.1333	−0.01	0.02	−0.01
1-11	0.1	88.5	0.6034	0.25	0	80.66	64.85	0.7941	0.6014	223.7	0.479	0.858	0	1.6921	3.0216	5.2150	−0.01	−0.06	0.02
1-12	0.1	88.5	0.6034	0.25	0	80.66	64.85	0.7941	0.6014	223.7	0.479	0.858	0.01946	1.6921	3.0592	5.2151	−0.01	−0.06	0.03
1-13	0.1	88.5	0.6034	0.25	100	80.66	61.87	0.7940	0.6012	229.7	0.479	0.858	0.01947	1.7417	3.1475	4.5916	−0.04	0.00	−0.01
3-1	0.1	98.5	0.0625	0.16	0	93.45	92.77	0.2894	0	188.2	0.524	0.870	0.15772	0.5179	0.8678	1.3771	0.00	−0.02	−0.00
3-2	0.1	98.5	0.0625	0.20	0	78.42	76.34	0.6682	0	190.6	0.536	0.794	0	0.9087	1.3138	2.1208	0.00	−0.02	0.00
3-3	0.1	98.5	0.0625	0.20	0	78.11	76.01	0.6732	0	190.8	0.536	0.794	0.40459	0.9091	1.6226	2.1180	0.00	−0.01	0.01
3-8	0.1	96.0	0.1842	0.16	0	79.37	78.54	0.6523	0	183.4	0.539	0.778	0.40312	0.5710	0.9141	1.1007	−0.00	−0.01	−0.01
3-9	0.1	96.0	0.1842	0.16	0	79.50	78.67	0.6501	0	183.3	0.539	0.778	0	0.5715	0.7723	1.1018	−0.00	−0.01	−0.00
3-10	0.1	96.0	0.1842	0.16	100	82.72	81.83	0.5898	0	182.3	0.537	0.788	0.35860	0.5926	0.9345	0.9745	−0.00	−0.00	−0.02
3-11	0.1	96.0	0.1842	0.16	100	83.04	82.17	0.5831	0	182.2	0.537	0.789	0	0.5953	0.8111	0.9760	−0.00	−0.00	−0.01

1, Ethanol–water; 3, air–water. $\Delta T_{V\infty} = T_{V\infty} - T_{s\infty}$. $\Delta W = W_{1Vi} - W_{1L}$. Φ'_{44}, Φ'_{34}, calculated by equations (44) and (34), respectively. Θ'_{35}, calculated by equation (35).

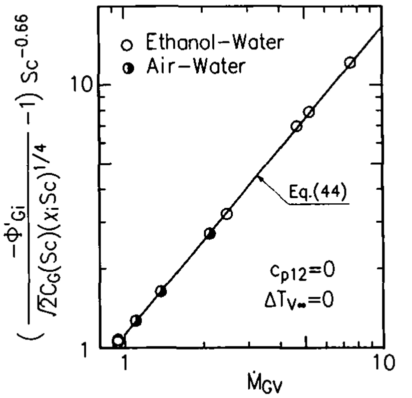

FIG. 1. Relation between $[-\Phi'_{Gi}/\sqrt{2}C_G(Sc)(\chi\ Sc)^{1/4}-1]Sc^{-0.66}$ and $\dot{M}_{GV}$.

examples of the comparisons of the similarity solution Φ'_{Gi} with equations (44) and (34) and Θ'_{GVi} with equation (35). As for Φ'_{Gi}, most of the data agree with equations (44) and (34) within an error of 2%, although the errors for a few data are a little more, except in the cases of Nos. 1-4 ~ 1-6, which are beyond the applicable range of equation (34). As for Θ'_{GVi}, most of the data agree with equation (35) within an error of 1%, although the errors for a few data are about 3%.

The Sh_x equation can be derived from equations (32) and (44) or equations (32) and (34) as

$$Sh_x = \{1+1.13Sc^{0.66}(\dot{M}_{GV})^{1.17}\} \times C_G(Sc)\left(\frac{\chi}{\omega}Gr_x\,Sc\right)^{1/4} \quad (45)$$

$$Sh_x = \left(\frac{2}{1+W_R}\right)^{0.5} W_R^{0.8}C_G(Sc)\left(\frac{\chi}{\omega}Gr_x\,Sc\right)^{1/4} \quad (46)$$

and the Nu_{cx} equation from equations (33) and (35) as

$$Nu_{cx} = [1+1.13Pr_V^{0.66}(\dot{M}_{GV})^{1.17}\{1-0.85c_{p12} \times (W_{1Vi}-W_{1L})\}]C_G(Pr_V)\left(\frac{\chi^+}{\omega}Gr_x\,Pr_V\right)^{1/4} \quad (47)$$

where the Grashof number defined by equation (42) is corrected by multiplying χ/ω in equations (45) and (46) and χ^+/ω in equation (47).

4. CONCLUSIONS

(1) As for the convective heat transfer in the case of forced-convection condensation, equation (20) by Rose and equation (24) by Fujii *et al.* have almost the same high accuracy, though their functional forms are different. However, the accuracy of equation (20) decreases in the case where the effect of the enthalpy diffusion term becomes marked, although its effect upon the heat flux at the cooling surface is small.

(2) As for the mass transfer coefficient in the case of forced-convection condensation, equation (19) by Rose, equation (23) by Fujii *et al.*, and equation (28), which has been derived from equation (24) by replacing Nu_c with Sh and Pr_V with Sc, have almost the same high accuracy, though their functional forms are different from each other.

(3) In the case of free-convection condensation, equation (44) for mass transfer has been derived from equation (35) for convective heat transfer, where the replacing χ^2/ω with χ/ω, which is a correction concerning the buoyancy force, is done as well as the replacing Nu_c with Sh and Pr_V with Sc. The applicable range of equation (44) is wider than that of equation (34) by Fujii, although their accuracy is almost the same.

REFERENCES

1. T. Fujii, H. Uehara, K. Mihara and T. Kato, Forced convection condensation in the presence of noncondensables—a theoretical treatment for two-phase laminar boundary layer, *Rep. Res. Inst. Ind. Sci. Kyushu Univ.* **66,** 53–80 (1977) (in Japanese).
2. J. W. Rose, Boundary-layer flow with transpiration on an isothermal flat plate, *Int. J. Heat Mass Transfer* **22,** 1243–1244 (1979).
3. J. W. Rose, Approximate equations for forced-convection condensation in the presence of a non-condensing gas on a flat plate and horizontal tube, *Int. J. Heat Mass Transfer* **23,** 539–546 (1980).
4. J. C. Y. Koh, Laminar film condensation of condensable gases and gaseous mixtures on a flat plate, *Proc. 4th U.S.A. Natn. Cong. Appl. Mech.*, Vol. 2, pp. 1327–1336 (1962).
5. E. M. Sparrow, W. J. Minkowycz and M. Saddy, Forced convection condensation in the presence of noncondensables and interfacial resistance, *Int. J. Heat Mass Transfer* **10,** 1829–1845 (1967).
6. T. Fujii, *Theory of Laminar Film Condensation*, pp. 36, 39, 40, 45, 61, 64, 65, 68. Springer, New York (1991).
7. T. Fujii, K. Shinzato and J. B. Lee, A proposal of a new equation for the mass concentration gradient at the vapor–liquid interface in the case of forced-convection laminar film condensation of a binary vapor mixture on a flat surface, *Engng Sci. Rep. Kyushu Univ.* **13,** 293–296 (1991).