PERGAMON

International Journal of Heat and Mass Transfer 41 (1998) 3657–3668

International Journal of
HEAT and MASS
TRANSFER

Non-absorbable gas effect on the wavy film absorption process

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Received 8 January 1997

Abstract

The performance of the absorber determines the COP of the absorption chiller. This paper deals with the heat and mass transfer characteristics for a falling film type absorber when non-absorbable gas (air) is present in the gas side. The study is based on a mathematical model which describes the heat and mass transports for the absorption process taking place on a falling wavy film flow. The results are compared with that of smooth film absorption as well as the results of wavy film absorption without the presence of non-absorbables. It is shown that wave enhances the absorption rates while the non-absorbables depress the absorption rates significantly. The present simulation is found to be in good agreement with previous experimental results. The correlations for heat and mass transfer coefficients are given. © 1998 Published by Elsevier Science Ltd. All rights reserved.

Nomenclature

A	surface area [m^2]
A_n, B_n	coefficients of expansion for waves
c	wave velocity [m s^{-1}]
C	LiCl concentration in weight percentage
C_a	air concentration in volume percentage
C_p	specific heat [kJ (kg^{-1} °C^{-1})]
D	mass diffusivity [m^2 s^{-1}]
g	gravitational acceleration
h	local film thickness [m], or enthalpy [kJ kg^{-1}]
h_m	mass transfer coefficient [m s^{-1}]
h_0	mean film thickness over a wavelength [m]
H_a	heat of absorption [kJ kg^{-1}]
M_{abs}	mass absorption rate per unit width [kg (m s^{-1})]
M_s	liquid flow rate [kg (m s^{-1})]
Nu	Nusselt number
p_v	vapor pressure
Q	heat transfer rate [kW m^{-1}]
Re	Reynolds number $= 4\Gamma_0/v$
Sh	Sherwood number
t	time [s]
T	temperature [°C]
u	x-direction velocity
v	y-direction velocity
V_0	characteristic velocity $= \Gamma_0/h_0$
x	coordinate parallel to the wall
y	coordinate normal to the wall.

Greek symbols

α	thermal diffusivity [m^2 s^{-1}]
Γ_0	mean volumetric flow rate per unit width [m^3 m s^{-1}]
η	$= y/h(\zeta)$
η_a	$= \eta - 1$
ζ	$= x - ct$
v	dynamic viscosity [kg m s^{-1}]
ρ	liquid density [kg m^{-3}]
ϕ	dimensionless wave amplitude.

Subscripts

eq	equilibrium condition
a	quantities associated with gas
in	inlet quantities
out	outlet quantities
s	quantities associated with liquid
w	wall conditions.

1. Introduction

Falling film absorption is a practical process applied in absorption heat pumps, chillers and air-conditioners.

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PII: S0017–9310(98)00061–1

This process is a coupled heat and mass transport problem, and the presence of the waves on the film and the presence of the air (acting as non-absorbables) in the gas phase are always involved. The existing theoretical studies on this problem include (1) smooth (waveless) film absorption without considering non-absorbable (or non-condensable) gas effects [1–4]; (2) smooth film absorption with non-absorbable gas effect considered [5]; and (3) wavy film absorption without considering non-absorbable gas effects [6].

The effects of non-absorbable gases on the absorption process share many similarities to the effects of non-condensable gases on the condensation process which has been studied theoretically [7, 8] and experimentally [9, 10]. The non-absorbable gases impacts the mass transfer process when the absorption of the vapor at the liquid–vapor interface drives a continuous vapor flow toward the interface while the non-absorbable gases are carried along. Since the interface is impermeable to them, the non-absorbable gases are then accumulated near the interface. The partial pressure of the vapor at the interface is hence reduced, and the adsorption rate is reduced in turn. The result for a smooth film model has shown by Yang and Chen [5] that even with a very low percentage of non-absorbable gases present in the ambient, whose concentration at the gas–liquid interface can be very large and the resulted reduction in mass absorption rate is significant.

The significant effect of waves on the absorption process has been reported [11–13]. Since the presence of waves on a falling liquid film is observed for almost all flow rates of practical importance [14, 15], a numerical model that accounts for its effect on the transfer rates of the absorption process is desired for the designer. A suitable model is given by Yang and Jou [6] whose results indicate that film waves have a strong effect on the absorption rate and the mass absorption rate can be doubled. They also suggested that a falling film absorber may give higher performance than a practical spray-on-horizontal-tubes type absorber for the reason that the waves are not prominent in a spray type absorber since the wavelength is about the same as the size of the tube diameter.

The problem exists as lack of a model that simultaneously considers the presence of both the waves and the non-absorbables in the absorption process. Since the equilibrium relations for the absorbent vapor pressure, temperature and concentration are highly nonlinear, which makes the nondimensionlization of the problem difficult. An hence, in this paper, the effect of non-absorbable gas on the wavy film absorption process is studied numerically. The absorption of the water vapor (absorbate) by a falling aqueous lithium chloride (absorbent) solution is chosen as a physical model problem for this study, which would be important for the modern open-cycle absorption solar cooling application [16] because the presence of non-absorbable gas is unavoidable.

2. Analysis

Figure 1 depicts the physical problem where a film of an absorbent solution flowing down a vertical plane and absorbing the ambient absorbate (refrigerant) vapor. The absorption process, taking place continuously in an absorber/evaporator unit, continuously evaporates the liquid refrigerant from the evaporator whereby the cooling capacity is delivered. The problem can be formulated mathematically using the coordinate system defined in Fig. 2.

The following assumptions are adopted:

(1) The liquid film flow is periodic.
(2) The liquid properties are assumed to be constant, since the variations of temperature and concentration are presumed to be small.
(3) The average mean film thickness is assumed to be constant, since the rate of the absorbed mass is much less than the mass rate of the main flow.
(4) Equilibrium of the species exists at the liquid–vapor interface.

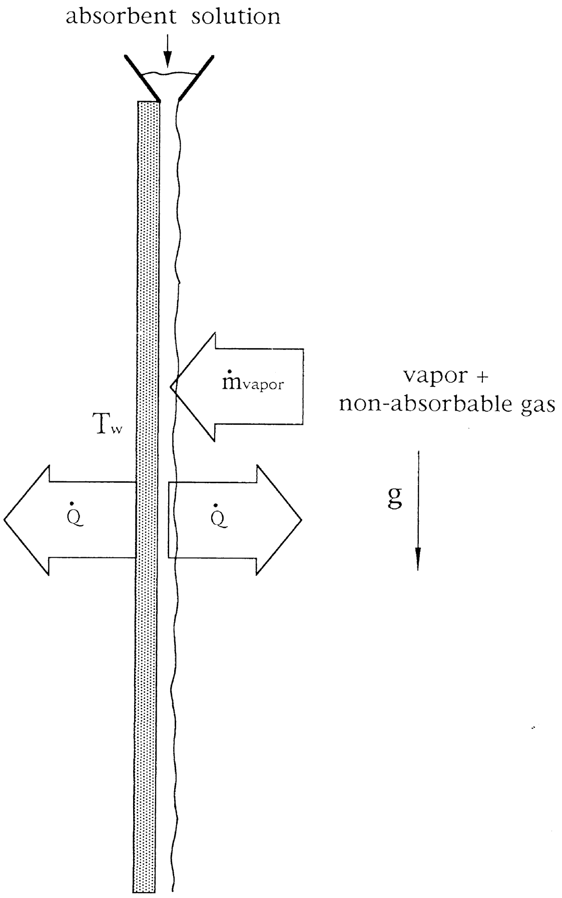

Fig. 1. Schematic of physical model problem.

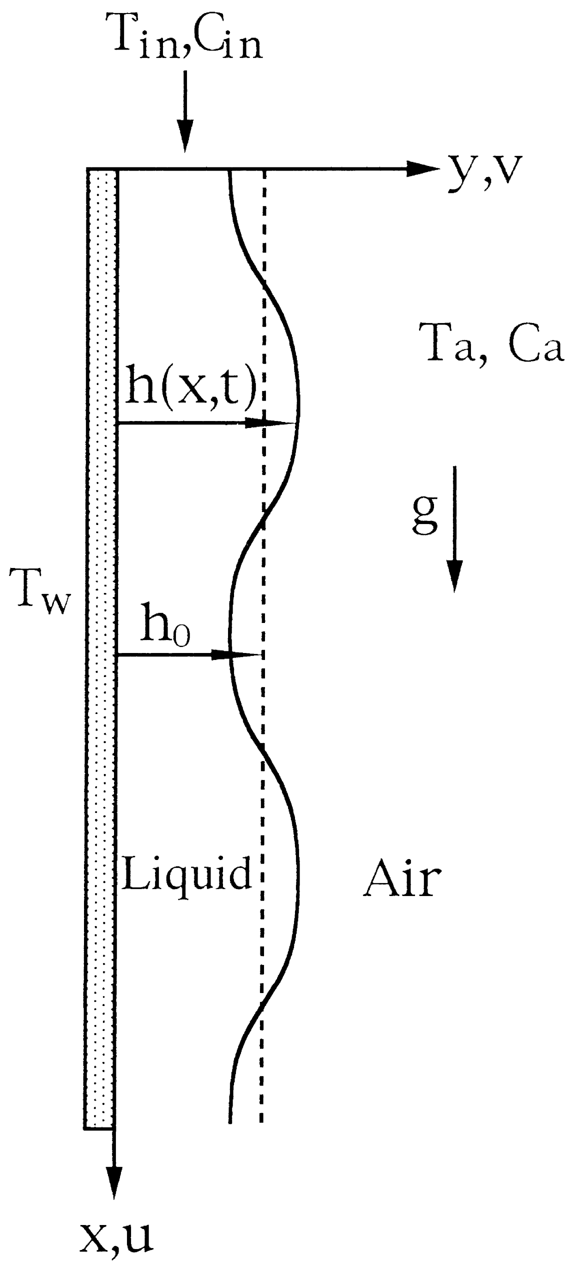

Fig. 2. Coordinate system.

(5) Diffusion is important only in the direction across the film since the Peclet number is practically large.
(6) Thermal effects of diffusion are negligible [17].

Then, the momentum equation can be solved as a priori due to the decoupled equations.

A previous wavy flow solution given by Yang and Wood [18] is suitable for the present application. The solutions were given as follows:

$$u = \frac{3}{2}V_0(2\eta-\eta^2)\left[1+\left(\frac{V_0}{c}-1\right)\phi-\left(\frac{V_0}{c}-1\right)\phi^2\right] \quad (1)$$

$$v = -3V_0h_0\frac{\partial\phi}{\partial x}\left\{-\left(\frac{V_0}{c}-1\right)(1-2\phi)(1+\phi)\left(\frac{\eta^2}{2}-\frac{\eta^3}{6}\right)\right.$$
$$\left.+\left[1+\left(\frac{V_0}{c}-1\right)\phi-\left(\frac{V_0}{c}-1\right)\phi^2\right]\left(\frac{\eta^2}{2}-\frac{\eta^3}{3}\right)\right\} \quad (2)$$

where the dimensionless free surface deflection, ϕ, is defined in a spectral expansion form, i.e. $\phi = \Sigma_{n=1}^{N}\,[A_n \sin 2n\pi\zeta + B_n \cos 2n\pi\zeta]$, and h_0 is the average film thickness over a wavelength such that the local film thickness can be expressed by $h(\zeta) = h_0(\zeta)(1+\phi)$. When the absorption process reaches a periodically-steady state, the ambient gas can be considered having a velocity equal to the interface velocity. This consideration is in corresponding to a much thicker momentum boundary layer than the concentration and the thermal boundary layers. Therefore, the gas velocities are:

$$u_a = \frac{3}{2}V_0\left[1+\left(\frac{V_0}{c}-1\right)\phi-\left(\frac{V_0}{c}-1\right)\phi^2\right] \quad (3)$$

$$v_a = -3V_0h_0\frac{\partial\phi}{\partial x}\left\{-\frac{1}{3}\left(\frac{V_0}{c}-1\right)(1-2\phi)(1+\phi)\right.$$
$$\left.+\frac{1}{6}\left[+\left(\frac{V_0}{c}-1\right)\phi-\left(\frac{V_0}{c}-1\right)\phi^2\right]\right\}. \quad (4)$$

The heat and mass transfer equations for the liquid film are:

$$\rho C_p\left(\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=\frac{\partial}{\partial y}\left(K\frac{\partial T}{\partial y}\right) \quad (5)$$

$$\rho\left(\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}\right)=\frac{\partial}{\partial y}\left(\rho D\frac{\partial C}{\partial y}\right) \quad (6)$$

and the suitable boundary conditions are

$$t = 0 \quad T = T_0(x,y)$$
$$C = C_0(x,y) \quad (7)$$
$$x = 0 \quad T = T_{in}$$
$$C = C_{in} \quad (8)$$
$$y = 0 \quad T = T_w$$
$$\frac{\partial C}{\partial y} = 0 \quad (9)$$
$$y = h \quad C = C_{eq}(T, P_v)$$
$$-k\frac{\partial T}{\partial n} = -k_a\frac{\partial T_a}{\partial n}+H_a\rho D\frac{\partial C}{\partial n} \quad (10)$$

where the interfacial normal vector is

$$\mathbf{n} = \frac{-\dfrac{\partial h}{\partial x}\mathbf{i}+1\mathbf{j}}{\sqrt{\left(\dfrac{\partial h}{\partial x}\right)^2+1}}. \quad (11)$$

The heat and mass transfer equations for the gas are:

$$\rho_a C_{P_a}\left(\frac{\partial T_a}{\partial t}+u_a\frac{\partial T_a}{\partial x}+v_a\frac{\partial T_a}{\partial y}\right)=\frac{\partial}{\partial y}\left(K_a\frac{\partial T_a}{\partial y}\right) \tag{12}$$

$$\rho_a\left(\frac{\partial C_a}{\partial t}+u_a\frac{\partial C_a}{\partial x}+v_a\frac{\partial C_a}{\partial y}\right)=\frac{\partial}{\partial y}\left(\rho_a D_a\frac{\partial C_a}{\partial y}\right) \tag{13}$$

and the suitable boundary conditions are

$$t=0,\quad T_a=T_{a,0}(x,y)$$

$$C_a=C_{a,0}(x,y) \tag{14}$$

$$x=0\quad T_a=T_{a\infty}$$

$$C_a=C_{a\infty} \tag{15}$$

$$y=h\quad T_a=T(x,h)$$

$$\frac{\partial C_a}{\partial n}=\frac{\partial C}{\partial n} \tag{16}$$

$$y=\infty\quad T_a=T_{a\infty}$$

$$C_a=C_{a\infty}. \tag{17}$$

For computational convenience, the transverse coordinate is transformed by

$$\eta=\frac{y}{h(\zeta)}=\frac{y}{h_0(1+\phi)} \tag{18}$$

and the air side transverse coordinate $\eta_a=\eta-1$ is further transformed by

$$\bar{\eta}=\frac{\eta_a}{\eta_a+L} \tag{19}$$

where L is an arbitrary transformation constant.

The transfer formed computational domain for $y=h$ and ∞ are transformed into $\eta=1$ and $\bar{\eta}=1$, respectively. Accordingly, the governing equations for liquid are transformed into

$$\rho C_p\left\{\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+\left[\frac{\eta}{1+\phi}(c-u)\frac{\partial\phi}{\partial\zeta}+\frac{v}{h}\right]\frac{\partial T}{\partial\eta}\right\}=\frac{1}{h}\frac{\partial}{\partial\eta}\left(\frac{K}{h}\frac{\partial T}{\partial\eta}\right) \tag{20}$$

$$\rho\left\{\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}+\left[\frac{\eta}{1+\phi}(c-u)\frac{\partial\phi}{\partial\zeta}+\frac{v}{h}\right]\frac{\partial C}{\partial\eta}\right\}=\frac{1}{h}\frac{\partial}{\partial\eta}\left(\frac{\rho D}{h}\frac{\partial C}{\partial\eta}\right) \tag{21}$$

and the initial and the boundary conditions become

$$t=0\quad T=T_0(x,y)$$

$$C=C_0(x,y) \tag{22}$$

$$x=0\quad T=T_{in}$$

$$C=C_{in} \tag{23}$$

$$\eta=0\quad T=T_w$$

$$\frac{\partial C}{\partial\eta}=0 \tag{24}$$

$$\eta=1\quad -k\frac{\partial T}{\partial n}=-k_a\frac{\partial T_a}{\partial n}+H_a\rho D\frac{\partial C}{\partial n}$$

$$C=C_{eq}(T,P_v). \tag{25}$$

The heat and mass transfer equations for the gas are transformed into:

$$\rho_a C_{P_a}\left\{\frac{\partial T_a}{\partial t}+u_a\frac{\partial T_a}{\partial x}+\left[\frac{(c-u_a)(\bar{\eta}-1)[\bar{\eta}(1-L)-1]}{(1+\phi)L}+\frac{(\bar{\eta}-1)^2 v_a}{hL}-\frac{(\bar{\eta}-1)^4}{\rho_a C_{P_a}h^2L^2}\frac{\partial k_a}{\partial\bar{\eta}}-\frac{2k_a(\bar{\eta}-1)^3}{\rho_a C_{P_a}h^2L^2}\right]\frac{\partial T_a}{\partial\bar{\eta}}\right\}=\frac{k_a(\bar{\eta}-1)^4}{h^2L^2}\frac{\partial^2 T_a}{\partial\bar{\eta}^2} \tag{26}$$

$$\rho_a\left\{\frac{\partial C_a}{\partial t}+u_a\frac{\partial C_a}{\partial x}+\left[\frac{(c-u_a)(\bar{\eta}-1)[\bar{\eta}(1-L)-1]}{(1+\phi)L}+\frac{(\bar{\eta}-1)^2 v_a}{hL}-\frac{(\bar{\eta}-1)^4}{\rho_a h^2L^2}\frac{\partial C_a}{\partial\bar{\eta}}-\frac{2D_a(\bar{\eta}-1)^3}{h^2L^2}\right]\frac{\partial C_a}{\partial\bar{\eta}}\right\}=\frac{\rho_a C_a(\bar{\eta}-1)^4}{h^2L^2}\frac{\partial^2 C_a}{\partial\bar{\eta}^2} \tag{27}$$

and boundary conditions become

$$t=0\quad T_a=T_{a,0}(x,\bar{\eta})$$

$$C_a=C_{a,0}(x,\bar{\eta}) \tag{28}$$

$$x=0\quad T_a=T_{a\infty}$$

$$C_a=C_{a\infty} \tag{29}$$

$$\bar{\eta}=0\quad T_a=T_{h=1}$$

$$\frac{\partial C_a}{\partial n}=\frac{\partial C_{\eta=1}}{\partial n} \tag{30}$$

$$\bar{\eta}=1\quad T_a=T_{a\infty}$$

$$C_a=C_{a\infty}. \tag{31}$$

The problem is solved numerically by a finite difference method. The computational grids are chosen to be denser in the entrance, the interface and the wall regions. The largest grid size is less than 1/10 of the wavelength, and the time step is less than 1/20 of the wave period. The chosen number of grids are (400 × 100) in the liquid region and (400 × 200) in the gas region after several tests of different grid sizes. The solutions are converged when periodicity conditions are present.

3. Results and discussion

The mass absorption rate can be calculated by

$$\dot{M}_{abs}=\dot{M}_{out}-\dot{M}_{in}. \tag{32}$$

Since the mass flow rate of the salt is constant, i.e.

$$\dot{M}_{\text{in}} \times C_{\text{in}} = \dot{M}_{\text{out}} \times C_{\text{out}}. \quad (33)$$

Equation (32) becomes

$$\dot{M}_{\text{abs}} = \dot{M}_{\text{in}} \left[\frac{C_{\text{in}}}{C_{\text{out}}} - 1 \right]. \quad (34)$$

The mass transfer coefficient, h_m, is then defined as

$$\dot{M}_{\text{abs}} = \rho h_m A [C_{\text{in}} - C_{\text{eq}}(T_w, P_v)] \quad (35)$$

where C_{eq} is the concentration when the liquid is in equilibrium with the wall temperature and the ambient vapor pressure. When the wall is long enough, the liquid concentration will approach to C_{eq}, which represents the lowest possible concentration in the absorption process.

The heat transfer rate is obtained by performing an energy balance over the entire control volume:

$$\dot{Q} = \dot{M}_{\text{in}} h_{\text{in}} + \dot{M}_{\text{abs}} H_a + \dot{M}_{\text{out}} h_{\text{out}}. \quad (36)$$

The heat transfer coefficient, h, is defined by

$$Q = hA[T_{\text{eq}}(C_{\text{in}}, P_v) - T_w] \quad (37)$$

where T_{eq} is the temperature when the liquid is in equilibrium with the inlet concentration and the ambient vapor pressure. T_{eq} represents the highest possible temperature in the absorption process.

Figure 3 shows, at the various down-stream locations, the bulk mean concentration as a function of time for a typical case with 5% non-absorbables gases and a film Reynolds number of 58. It is shown that the bulk mean concentration is periodic and it has the same period of the waves. The time averaged interfacial and bulk mean temperatures of the liquid along the flow direction are shown in Fig. 4. Figure 5 shows a similar plot for the concentrations.

The time averaged total absorption rate for various contact lengths is shown in Fig. 6. It can be seen that the absorption rates in a wavy film are much larger than those in a smooth film. Since the increase of the contact surface area by the presence of wave is only about 10% [19], therefore it is not the dominant effect for the increase of the adsorption rates. The main reason for the increase of the absorption is due to the transverse convection present in the wavy film flow [14]. Note that the transverse convection is not possible in a smooth film flow. Also presented in Fig. 6 is the experimental data given by Yang and Wood [20]. The present model shows a reasonably good agreement with the data.

Figures 7 and 8 provide the comparisons on the absorption rates and heat transfer rates, respectively, for various flow rates. Higher flow rates give higher heat and mass transfer rates for the practical range of $Re < 200$. The effects of the nonabsorbable gases on mass and heat transfer rates are illustrated in Figs 9 and 10,, respectively. It is worth noting that even with a very low percentage of the non-absorbable gases present in the ambient, whose concentration at the gas–liquid interface can be very large and the resulted reduction in mass absorption rate is very significant. The results are further compared with the results of the experimental data and the smooth film absorption for a fixed contact length of 0.85 m as shown in Figs 11 and 12. The deviation of the present result from the data in Fig. 12 is due to that the gas domain is considered half infinite in the model while

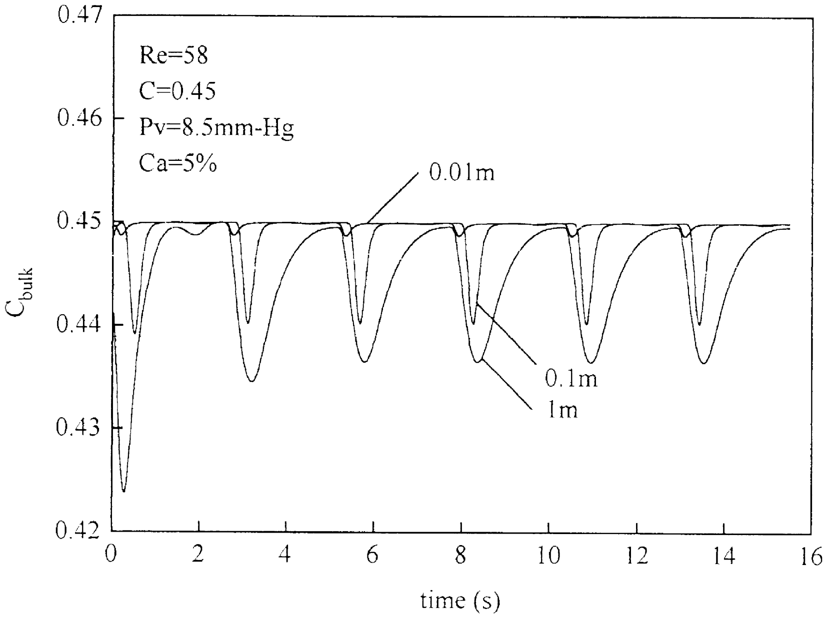

Fig. 3. Variation of the bulk mean concentration along with time.

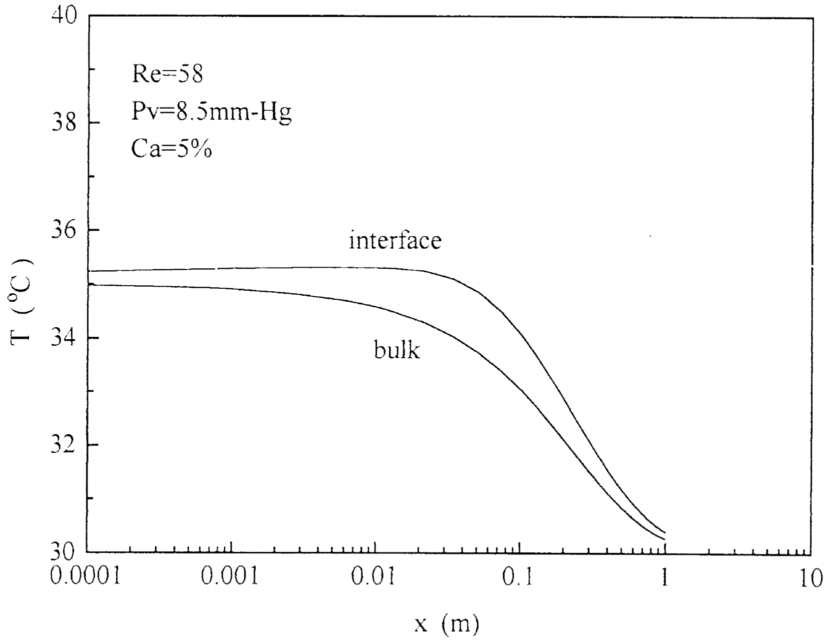

Fig. 4. Variation of the film temperature along with the flow direction.

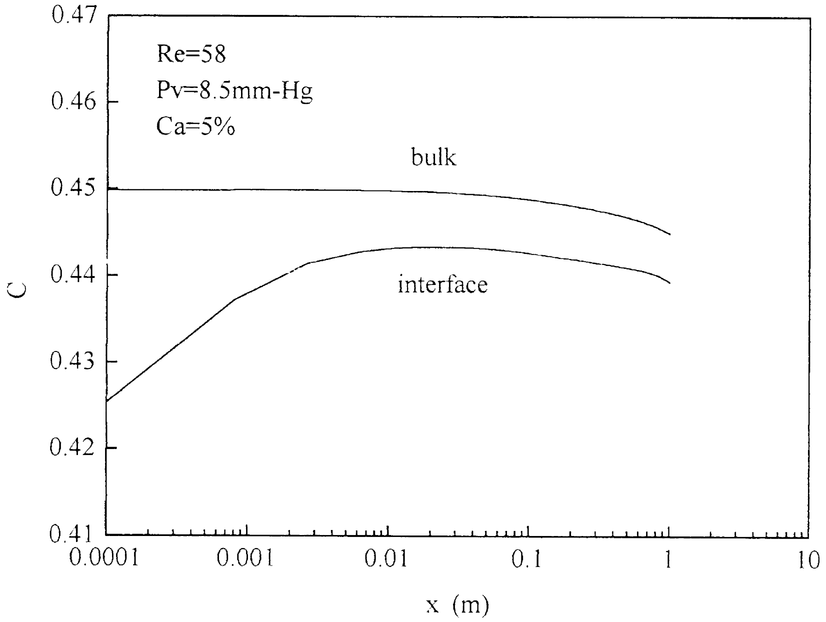

Fig. 5. Variation of the film concentration along with the flow direction.

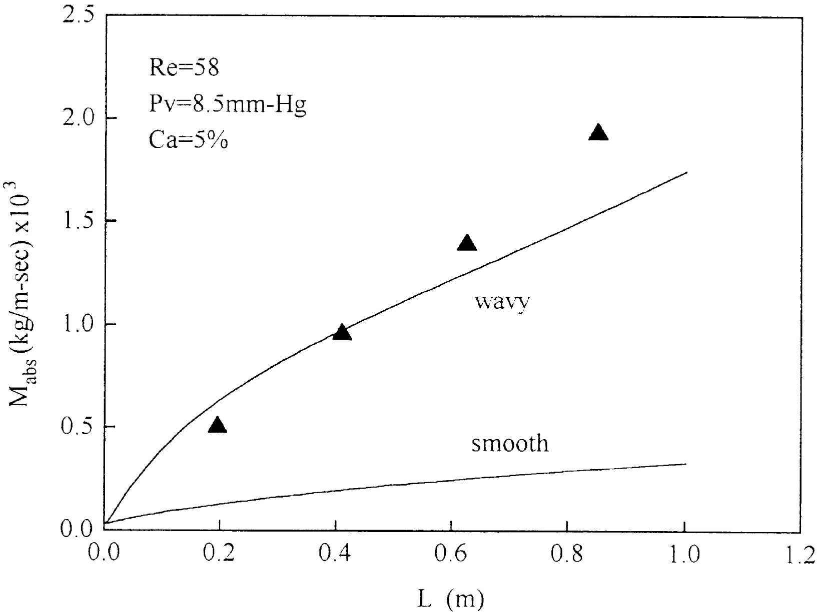

Fig. 6. Comparison of the present work with the smooth film model and the experimental results. (Data from [20].)

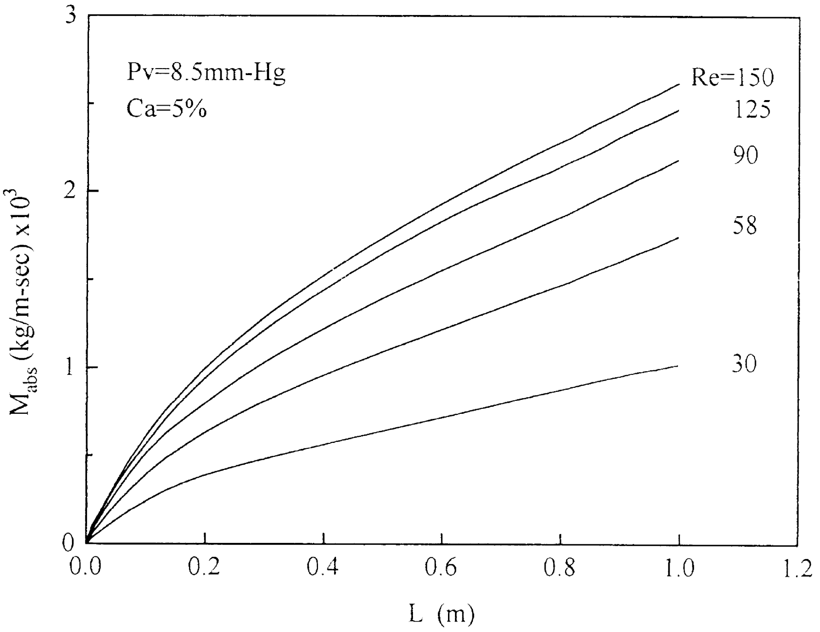

Fig. 7. The effect of flow rate on the cumulative absorption rate.

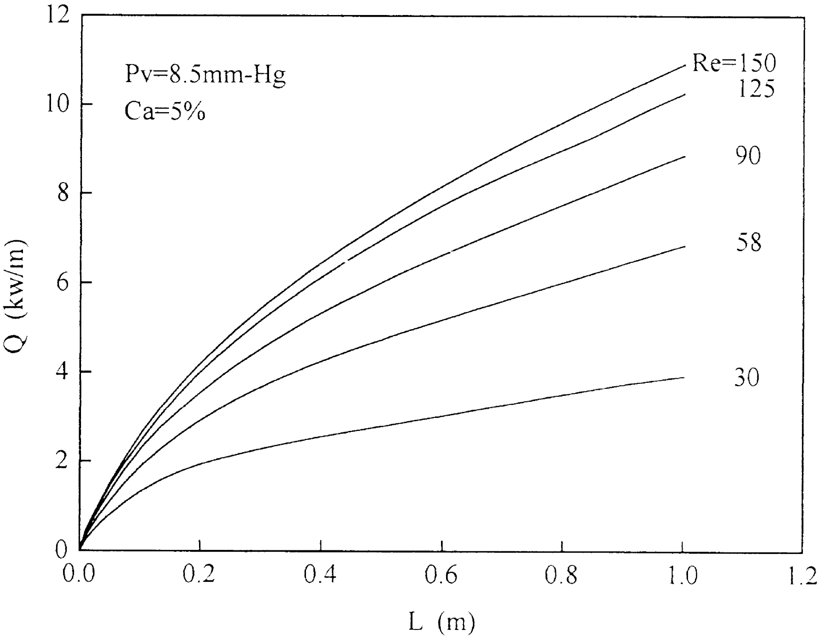

Fig. 8. The effect of flow rate on the cumulative heat transfer rate.

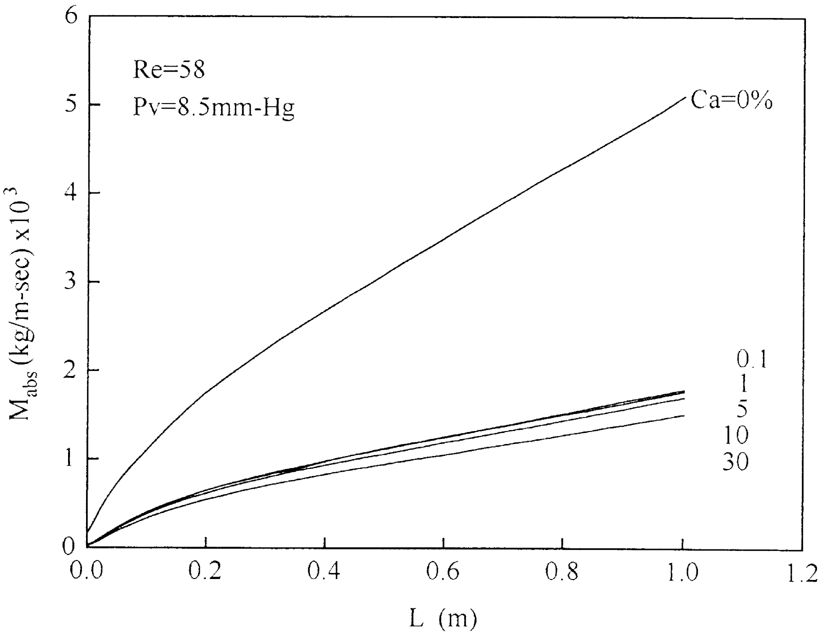

Fig. 9. The effect of non-absorbable concentration on the cumulative absorption rate.

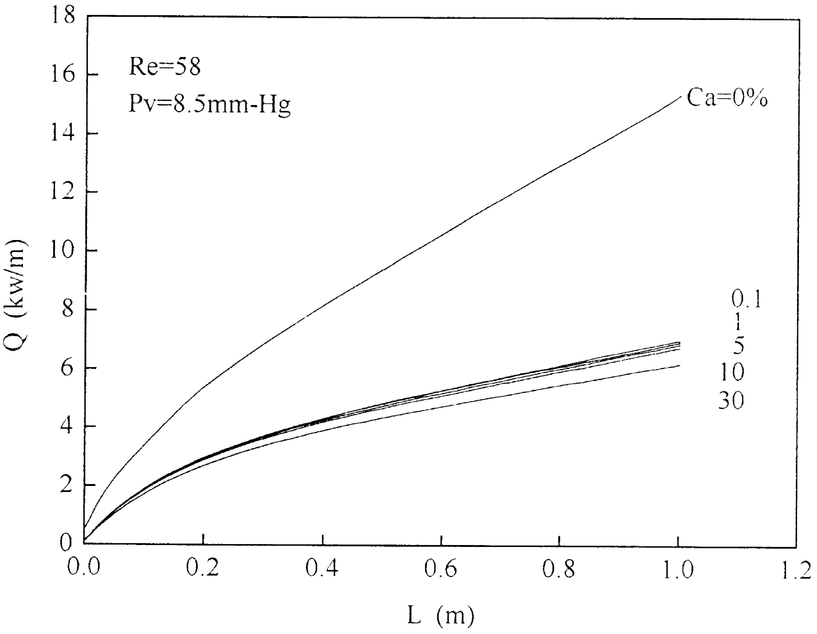

Fig. 10. The effect of non-absorbable concentration on the cumulative heat transfer rate.

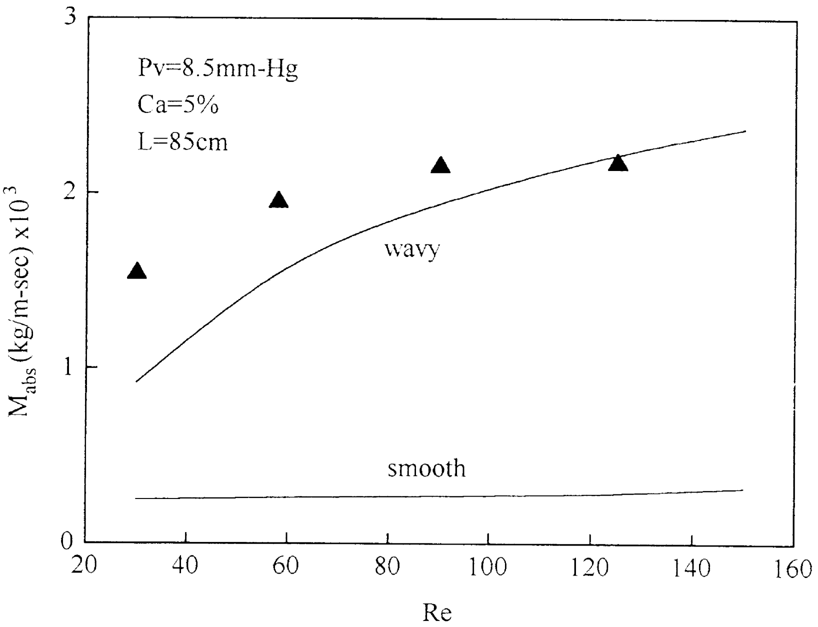

Fig. 11. Comparison of the absorption rate for Reynolds number effect. (Data from [20].)

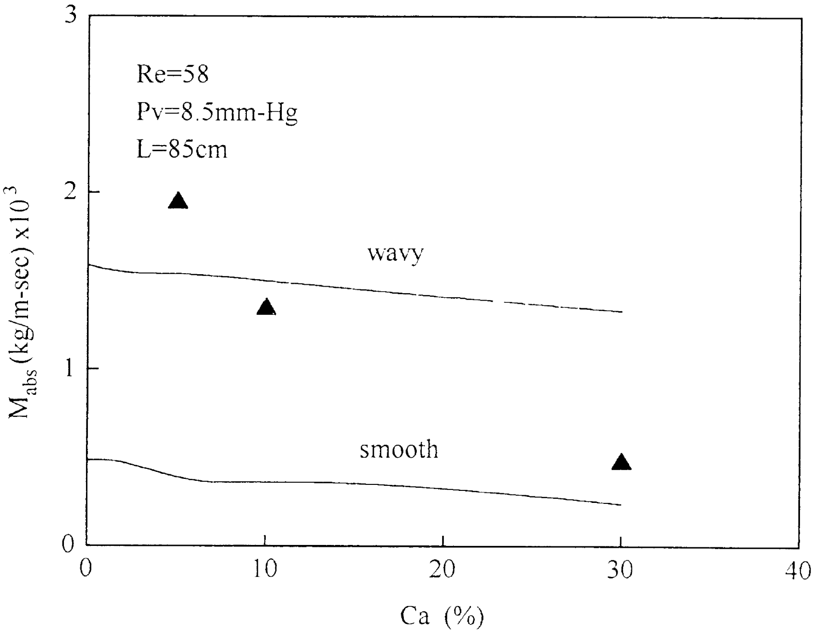

Fig. 12. Comparison of the absorption rate for non-absorbable effect. (Data from [20].)

the experimental gas domain is within a confined channel of only two inches thick. The absorption rates increase with increased flow rates while decrease with increased non-absorbable gas concentrations. The mass transfer coefficients corresponding to Figs 11 and 12 are given in Figs 13 and 14, respectively.

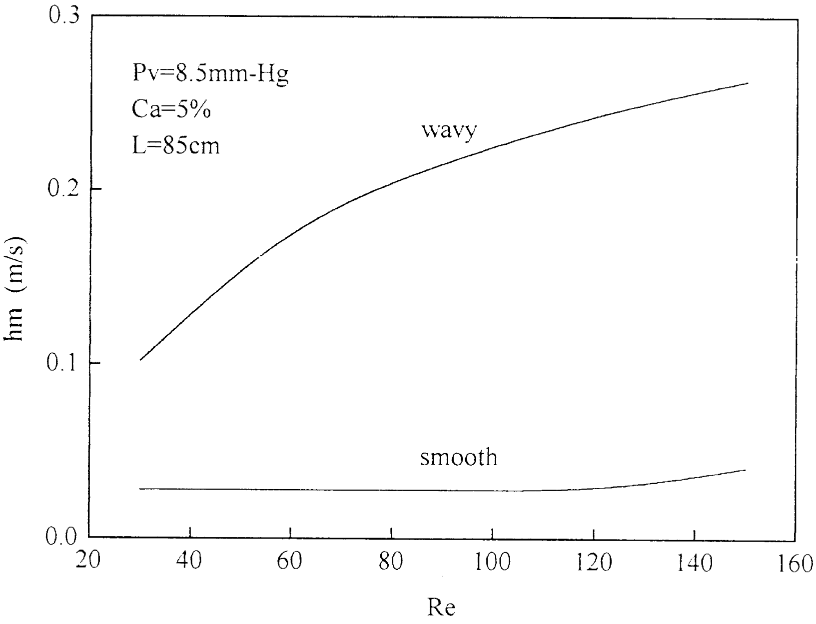

Fig. 13. Mass transfer coefficient for various flow rates.

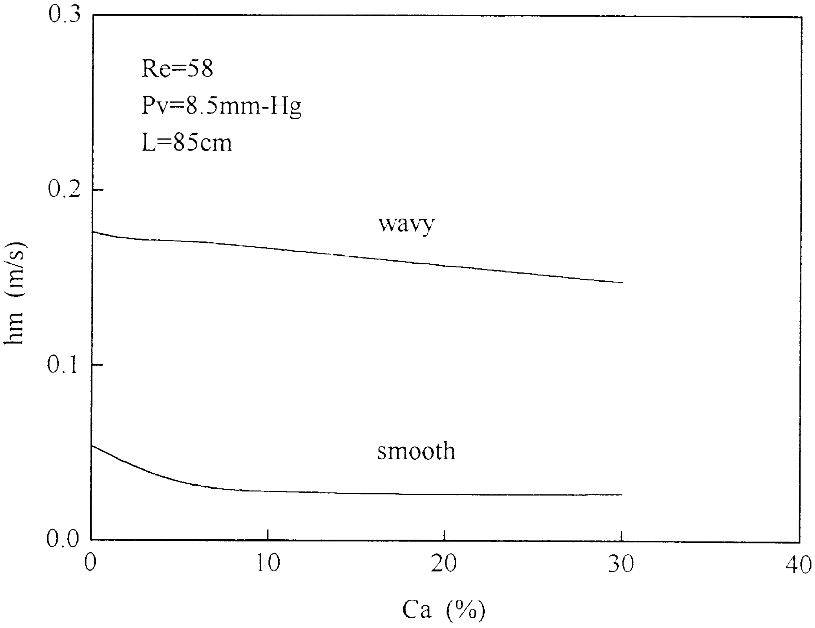

Fig. 14. Mass transfer coefficient for various non-absorbable concentrations.

The dimensionless heat and mass transfer coefficients can be defined, respectively, as

$$Nu = \frac{hL_c}{k} \tag{38}$$

$$Sh = \frac{h_m L_c}{D} \tag{39}$$

where $L_c = (\nu/g)^{1/3}$ is the characteristic length for a film [14]. The present study suggests the following correlations

$$Nu = 10^{-4.797} Re^{0.615}\, C_a^{-0.0211} \tag{40}$$

$$Sh = 10^{-0.448} Re^{0.579}\, C_a^{-0.0286}. \tag{41}$$

4. Conclusions

The study of the effects of both the waves and the non-absorbable gases on a falling film absorption process is given in this paper. The results indicate that even a very low percentage of the non-absorbable gases can drastically reduce the absorption rates, and the presence of waves can significantly increase the absorption rates. The absorption rates decrease with increased non-absorbable contents while increasing with increased flow rate. The correlations for heat and mass transfer coefficients are given, which would be valuable for designing absorbers.

Acknowledgement

The authors gratefully acknowledge the financial support of the National Science Council, ROC in supporting this research under the contract NSC 84-2212-E-110-002.

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