EVAPORATION OF WATER FROM A WETTED VERTICAL WAVY SURFACE

Jamaleddin O. Esalah, Mohamed M. Saied* and Mohamed M. Youssef**

University of Tripoli, Department of Materials & Metallurgical Engineering

* University of Tripoli, Department Chemical Engineering, Libya

** Polymers research center, Tripoli, Libya

E-mail: jesalah@yahoo.com

الملخص

يقدم هذا البحث دراسة نظرية لعملية تبخير الماء بطريقة الحمل الحراري الطبيعي (الحر) من سطح متموج مبلل بالماء على وسط راكد مكون من الهواء الجاف ومخاليط مختلفة من الهواء وبخار الماء والبخار المحمص. السطح بقي عند درجة حرارة ثابتة وتركيز ثابت.

تم اشتقاق المعادلات التفاضلية الجزئية التي تحاكي هذه الظاهرة وحلت هذه المعادلات باستخدام (نهج الفرق المحدود) بعد أن تم تحوير السطح من متموج إلى مسطح. تمت دراسة تأثير سعة الموجة للسطح المتموج على معدل التبخر وكذلك على درجة حرارة الإنقلاب. كما تمت دراسة تأثير درجة حرارة وتركيب وسط التبخير على معدل التبخر.

النتائج أثبتت أن معدل التبخر من الأسطح المتموجة أقل من الأسطح المسطحة عند نفس الظروف. كما أن معدل تبخر الماء يزداد بزيادة درجة حرارة الوسط. ومعدل التبخر عند استخدام الهواء الجاف أعلى من معدل التبخر عند استخدام البخار المحمص إلى عند درجة حرارة الإنقلاب وبعدها يصبح معدل التبخر باستخدام البخار المحمص هو الأعلى. سعة موجة السطح المتموج لم يكن لها أي تأثير على درجة الإنقلاب.

ABSTRACT

This paper presents the results of a theoretical study of the evaporation of the most common solvent, namely, water, by natural convection from a wet vertical wavy surface into stagnant streams of dry air, unsaturated mixtures of air and vapors, and super heated vapors. The surface is maintained at uniform wall temperature and constant wall concentration. A simple coordinate transformation is employed to transform the complex wavy surface to a rather simpler flat plate. A marching finite-difference scheme is used to solve the partial differential equations that describe the evaporation process. The effect of the amplitude of the wavy surface on the rate of evaporation and the inversion temperature, as well as the effect of ambient temperature and free stream composition are investigated. The results showed that the rate of evaporation from a wavy surface is significantly lower than that from a flat plate under the same conditions. The rate of evaporation of water increases as the ambient temperature increases and it is higher in pure air than that in superheated vapor up to the inversion temperature. Above this temperature the rate of evaporation becomes higher in superheated vapor than in pure air. The amplitude of the wavy surface showed no effect on the inversion temperature.

KEYWORDS: Evaporation; Natural (free) Convection; Wavy Surface; Combined Heat and Mass transfer; Inversion Temperature.

INTRODUCTION

The evaporation by natural convection phenomena find several applications in drying processes of wet materials from regular and irregular surfaces. The complex nature of this phenomenon which involves simultaneous heat and mass transfer has attracted the interest of many researchers in this field. Many authors studied the behavior of natural convection from regular surfaces due to its importance in many chemical processes [1-4]. Others studied this phenomenon from irregular surfaces such as surfaces with wavy geometry [5-10]. The evaporation process of solvents such as water into their own vapors, air and mixtures thereof has received considerable attention due to wide range of industrial applications. As a result of such interest super heated vapor (steam) has been recommended as an attractive drying medium for materials not sensitive to high temperatures.

Evaporation process of water and other solvents has been investigated experimentally by Chu *et al* [11] into their superheated vapors. Yoshida and Hydo [12] carried out several experiments on a wetted wall column with count current water and air laminar flow. They found that mass flow rates of air as the drying agent slightly affected the inversion temperature. Chow and Chung [13] studied numerically the steady state evaporation of water into a laminar flow of air, humid air, and superheated steam. They reported the inversion temperature at about 250$\circ$C. At the same mass flow of the free stream and at low free stream temperatures water evaporates at a faster rate in dry air than in humid air and superheated steam. This trend reversed itself at high stream temperatures. Chow and Chung [14] extended their study for water evaporation into a turbulent stream of air, humid air, and superheated steam. Their results showed that for turbulent flow conditions of the free stream the inversion temperature was 60$\circ$C lower than that for the laminar case, which is 190$\circ$C.

Hasan *et al* [15] carried out a theoretical study of laminar evaporation of water and other solvent from a horizontal flat surface into streams of air, saturated and superheated vapors. For the air-water system, their results agree with those of Chow and Chung. Haji and Chow [16] experimentally measured the rate of water evaporation from a horizontal flat surface into a turbulent stream of hot air and superheated steam at different free stream mass fluxes and temperatures. Their measurements of the rate of evaporation of water into air were a little higher than those found by numerical investigation. They reported value of inversion temperatures between 170 and 220$\circ$C, which are in good agreement with those analytically found by Chu *et al*[11].

Sheikholislami and Watkinson [17] studied the effect of humidity (water and vapor mixture) and superheated steam at different temperatures on the rate of water evaporation. Their experimental findings confirmed the existence of an inversion temperature above which the rate of evaporation of water increased with increased steam content in air. Schwartz and Brocker [18] studied analytically the same effect with the assumption that heat is transferred from the free stream to the liquid only by convection and that no heat flux between wall and liquid took place.

Inversion temperature for adiabatic evaporation of water from a horizontal surface into steam-air mixtures and superheated steam with constant flow rates was investigated by Volchkov *et al* [19]. Their results showed that lower concentration of steam in steam-air mixtures increases the inversion temperature.

The present work was motivated by the few research studies reported in the literature regarding irregular geometry such as wavy surfaces. The sinusoidal surface considered here can be considered as a good approximation to a wide range of wavy surfaces by changing the amplitude of the sine wave. The transformation procedure proposed by Yao [5] is adopted here to transform the sinusoidal wavy surface into the flat one. Finite difference method is used to solve numerically the set of partial equations resulted from the mathematical formulation of the problem.

The results of the present study will be compared with the experimental findings by Brodowicz [1] and those of the analytical results by Yao [7] and Bottemanne [2] for vertical wavy and flat surfaces, respectively.

Mathematical Formulation of the Problem

The transformation technique proposed by Yao [5] is applied here to transform the sinusoidal wavy surface into a flat one. The problem considered here involves natural convection on a semi-infinite isothermal vertical wavy plate as shown in Figure (1).

Thermo-physical properties are assumed constant except for the density variations of the buoyancy term in the x-momentum equation. The surface of the plate is described by the following equation,

$$y = \overline{x}(\overline{\sigma}) \tag{1}$$

The plate is situated in an otherwise quiescent fluid with a temperature T_∞ and mass fraction C_∞. The plate is maintained at T_w. The characteristic length associated with the wavy surface is ℓ. The x-coordinate is measured from the leading edge of the plate and the y-coordinate is measured vertical to the x-coordinate, as in Figure (1).

Steady state evaporation of water into stagnant pure air, unsaturated air, and superheated steam is investigated. The pressure of the free stream is atmospheric. It is assumed that the surface-fluid interface is stationary and no energy supplied from the back of the surface. Hence, the energy required for the evaporation of water must come from the free stream itself.

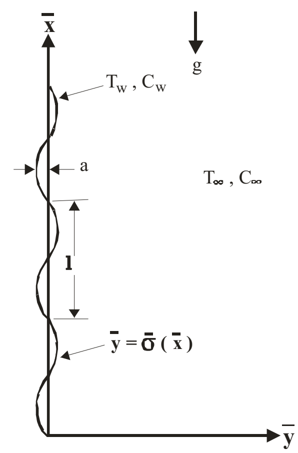

Figure 1: **Schematic diagram of the physical system**

The dimensional governing equations are the continuity, the Navier- Stockes equations, the energy equation and the species equation in two-dimensional Cartesian coordinates(x,y). The flow is assumed to be steady, and the fluid to Newtonian with constant properties except for density in the momentum equation (Boussinesq approximation).

Five differential equations in dimensional form describe the dynamics of the system:

continuity equation,

$$\frac{\partial \bar{u}}{\partial \bar{x}} + \frac{\partial \bar{v}}{\partial \bar{y}} = 0 \quad (2a)$$

x-momentum equation,

$$\rho \bar{u}\frac{\partial \bar{u}}{\partial \bar{x}} + \rho \bar{v}\frac{\partial \bar{u}}{\partial \bar{y}} = -\frac{\partial P}{\partial \bar{x}} + \mu(\frac{\partial^2 \bar{u}}{\partial \bar{x}^2} + \frac{\partial^2 \bar{u}}{\partial \bar{y}^2}) - \rho g \quad (2b)$$

y-momentum equation,

$$\rho \bar{u}\frac{\partial \bar{v}}{\partial \bar{x}} + \rho \bar{v}\frac{\partial \bar{v}}{\partial \bar{y}} = -\frac{\partial P}{\partial \bar{y}} + \mu(\frac{\partial^2 \bar{v}}{\partial \bar{x}^2} + \frac{\partial^2 \bar{v}}{\partial \bar{y}^2}) \quad (2c)$$

energy equation,

$$\bar{u}\frac{\partial \bar{T}}{\partial \bar{x}} + \bar{v}\frac{\partial \bar{T}}{\partial \bar{y}} = \alpha(\frac{\partial^2 \bar{T}}{\partial \bar{x}^2} + \frac{\partial^2 \bar{T}}{\partial \bar{y}^2}) \quad (2d)$$

species equation,

$$\bar{u}\frac{\partial \bar{C}}{\partial \bar{x}} + \bar{v}\frac{\partial \bar{C}}{\partial \bar{y}} = D(\frac{\partial^2 \bar{C}}{\partial \bar{x}^2} + \frac{\partial^2 \bar{C}}{\partial \bar{y}^2}) \quad (2e)$$

For $\beta\Delta T \langle\langle 1$ and $\beta^*\Delta C \langle\langle 1$, where ΔT and ΔC are temperature and concentration differences, the Boussinesq approximation may be employed, giving;

$$g(\rho_\infty - \rho) = g\beta\rho(T - T_\infty) = g\beta^*\rho(C - C_\infty) \quad (3)$$

Where, $\beta = -\frac{1}{\rho}(\frac{\partial \rho}{\partial T})_{P,C}$ and $\beta^* = -\frac{1}{\rho}(\frac{\partial \rho}{\partial C})_{T,P}$

In the momentum equation, the local static pressure P may be broken down into two terms; one due to the hydrostatic pressure in the ambient medium, P_∞, and the other due to motion of the fluid, P,

$$P = P_\infty + \bar{P} \quad (4)$$

where $P_\infty = -\rho_\infty g\bar{x}$ if the gravitational force is acting in the negative x-direction.

Hence, $$\frac{\partial P}{\partial \bar{x}} = \rho_\infty g + \frac{\partial \bar{P}}{\partial \bar{x}} \quad (5)$$

And $$\frac{\partial P}{\partial \bar{y}} = \frac{\partial \bar{P}}{\partial \bar{y}} \quad (6)$$

The governing equations are transformed using the parameters proposed by Yao [5] and employed by many authors.

The governing equations in dimensionless form are:

$$(4x)\frac{\partial u}{\partial x} + (2u - y)\frac{\partial u}{\partial y} + \frac{\partial v}{\partial y} = 0 \quad (7)$$

$$(4x)u\frac{\partial u}{\partial x} + (v - yu)\frac{\partial u}{\partial y} + (2 + \frac{4x\sigma'\sigma''}{1+\sigma'^2})u^2 = \frac{(\theta + R\psi)}{1+\sigma'^2} + (1+\sigma'^2)\frac{\partial^2 u}{\partial y^2} \quad (8b)$$

$$(4x)u\frac{\partial \theta}{\partial x} + (v - yu)\frac{\partial \theta}{\partial y} = \frac{1+\sigma'^2}{Pr}\frac{\partial^2 \theta}{\partial y^2} \quad (8c)$$

$$(4x)u\frac{\partial\psi}{\partial x}+(v-yu)\frac{\partial\psi}{\partial y}=\frac{1+\sigma'^2}{Sc}\frac{\partial^2\psi}{\partial y^2} \quad (8d)$$

Where, $\theta=\dfrac{T-T_\infty}{T_w-T_\infty}$, $\psi=\dfrac{C-C_\infty}{C_w-C_\infty}$, $\sigma'=\dfrac{d\bar{\sigma}}{d\bar{x}}=\dfrac{d\sigma}{dx}$,

$Gr=\dfrac{g\ell^3\beta(T_w-T_\infty)}{\nu^2}$, $Gr_c=\dfrac{g\ell^3\beta^*(C_w-C_\infty)}{\nu^2}$, and $R=\dfrac{Gr_c}{Gr}$

It is clear that the buoyancy term in the momentum equation is due to the combined effect of thermal and mass diffusion.

The velocity components, u and v are parallel to x and y axes, respectively, and is not parallel nor perpendicular to the wavy surface.

The boundary conditions are,

At $y=0$ $u=v=0$ and $\theta=\psi=1$

At $y\to\infty$ $u\to 0$, $\theta\to 0$ and $\psi\to 0$

The boundary condition $v=0$ at $y=0$, is strictly valid only for low mass transfer rate.

For high mass transfer rate, the velocity, v, at the surface is:

$$v|_w=(1+\sigma'^2)^{\frac{1}{2}}\frac{\bar{w}_n|_w}{\left(\frac{\beta g\Delta T\nu^2}{4\bar{x}}\right)^{\frac{1}{4}}} \quad (9)$$

The case when the ambient is a Superheated Vapor

The governing equations describing this problem are equations (7, 8b &8c) after dropping, the species equation and the buoyancy term due to mass diffusion from the momentum equation.

Boundary Conditions

- ***For the case when the ambient is pure air or unsaturated air:***
- at the surface (isothermal wall): $y=0$

  $u=0$ $\theta=1$ $\psi=1$

and $$v|_w=\frac{D}{c_w.\nu}(c_w-c_\infty)(1+\sigma'^2)^{1/2}\left.\frac{\partial\psi}{\partial y}\right|_{y=0} \quad (10)$$

According to Dalton's law and by assuming the air–vapor mixture is an ideal gas mixture, the concentration of vapor can be evaluated by:

$$c(x,0)=c_1=\frac{M_v/M_a}{P/P_{vs}+M_v/M_a-1} \quad (11)$$

Where; P_{vs} is a vapor pressure.

- at the free stream: $y\to\infty$

  $u\to 0$ $\theta\to 0$ and $\psi\to 0$

- ***For the case when the ambient is Superheated vapor:***

In this case, there is no mass diffusion body force and the problem reduces to pure heat convection, R=0

- At the surface (isothermal wall): $y=0$, $u=0$ $\theta=1$

and $$v|_w=\frac{k}{\rho.h_{fg}.\nu}(T_w-T_\infty)(1+\sigma'^2)^{1/2}\left.\frac{\partial\theta}{\partial y}\right|_{y=0} \quad (12)$$

At the isothermal surface, the interfacial temperature T_w is approximately equal to the saturation temperature of the vapor at one atmosphere, which is always considered, less than that of ambient stream.

- At the free stream: $y \rightarrow \infty$, $u \rightarrow 0$ $\theta \rightarrow 0$

Evaporation rate:

The average evaporation rate, $\overline{\dot{m}}_{ev}$ for a wet surface of length (s) is defined as:

$$\overline{\dot{m}}_{ev} = \frac{1}{s}\int_0^x \dot{m}(x)ds = \frac{\rho}{s}\int_0^x \dot{v}(x)ds$$
$$= \frac{\rho}{s}\int_0^x \dot{v}(x)(1+\sigma'^2)^{1/2}dx \tag{13}$$

$$\overline{\dot{m}}_{ev} = \frac{Gr^{1/4}.K}{h_{fg}}(T_w - T_\infty)\frac{1}{s}\int_0^x \left[\frac{(1+\sigma'^2)}{(4x)^{1/4}}\frac{\partial\theta}{\partial y}\right]_{y=0} dx \tag{14}$$

Where: $$s = \int_0^x (1+\sigma'^2)^{1/2} dx \tag{15}$$

Physical properties

If the drying media is air or air-vapor mixture, since there is no energy supplied from the back of the surface, the interfacial temperature should be equal to the wet bulb temperature of the free stream. Hence it is reasonable to assume the temperature to be constant along the surface. For the case when the free stream is pure superheated vapor, the interfacial temperature should be equal to the saturation temperature of the vapor at one atmosphere.

ince the physical properties in the natural convection boundary layer change both with temperature and mass fraction, to avoid costly variable-property solution another simplification is effected by evaluating the thermo- physical properties ρ, C_p, μ, k and D at reference state.

In the reference state method, the reference temperature and mass fraction are defined as:

$$T_r = T_w + r(T_\infty + T_w) \tag{16}$$

$$C_r = C_w + r(C_\infty + C_w) \tag{17}$$

Where r =1/3 used in this work as the reference state, it is known as the 'one-third rule', which has gained popularity in convective heat transfer. From previous studies, it was appeared that the one third rule approximation worked very well, even at very high temperature and when the free stream is mostly air, Chow and Chung [13]. For water-air system, Haraple's [20] correlations are used to calculate the component and mixture thermo-physical properties at the reference temperature and mass fraction.

If we consider the case when the evaporation is into an unsaturated air, then the governing equations are the equations (7, 8b – 8d)). Whereas the energy equation and the species equation are liner in θ and ψ, respectively, while the momentum equation

(8b), is nonlinear in terms of $u.u_x$, $u.u_y$ and u^2 where; $u_x = \left(\partial u / \partial x \right)$. A successful method for linearizing non-linear terms; the Newton-Raphson method [21 & 22], is used in this work.

RESULTS AND DISCUSSION

Numerical results are obtained for the wavy surface which is presented by the following dimensionless equation

$\sigma(x) = \alpha \sin(2\pi x)$ (18)

A fully implicit marching finite-difference scheme was used to solve the coupled governing equations for u, v, θ and ψ. The axial convection terms are approximated by the forward difference and the transverse convection and diffusion terms are approximated by the central difference. The y-grid size was fixed at 0.02, and the x-grid size at 0.025. The singularity at x = 0, has been removed by scaling, and therefore, the computation can be started from x = 0 and then marches downstream. At every x-station, the computations are iterated until the difference between two iterations of the variables u, v, θ and ψ becomes less than 10^{-5}.

By changing the dimensionless amplitude α we can study the effect of geometry on the natural convection of heat as well as mass transfer at ambient and other conditions.

Figures (1-5) case (a) and (b), illustrate the dimensionless temperature and velocity profiles for a vertical flat (α = 0) and wavy (α = 0.1) surfaces at nodes (x =1.5 and x = 2.0) and trough (x = 1.75) and crest (x = 2.25). These compare very well with the results obtained by Yao [5]. The difference between profiles near flat surface and that near trough and crest of wavy surface is very small. Furthermore, the profiles near trough and crest of the wavy surfaces differ only slightly for each of case (a) and (b). Figure (2b) shows excellent agreement between results presented by Bottemanne [2] and the present work for Pr = 0.71. Figures (3 a&b) show that the normal velocity, v, profiles near the trough and the crest are greater than that of the nodes of wavy surface. This means that the local heat transfer rates are greater near the trough and the crest than near the nodes. Figures (4a&b) demonstrate the dimensionless axial velocity u profiles at the trough and the crest for the wavy surface (α = 0.1) which differ slightly from that of vertical surface (α = 0). However the boundary layer thickness near the nodes is more than that near the crest and trough where the local heat transfer rate is larger. The present results showed excellent agreement with that presented by Yao [5]. Figure (5) compares the results of the present study with that of the experimental results of Brodowicz [1] regarding the dimensional axial velocity for vertical flat surface at positions (x = 2.0 cm and 12.0 cm) and as can be seen a good agreement is demonstrated.

Figures (6) show the dimensionless local heat transfer rates and for the wavy surface at (α = 0.1 and 0.2 and Pr = 1.0). From these figures it is clear that increasing the wave length ratio increases the rate of the local heat transfer rate.

Results of evaporation rate of water from wetted stationary wavy surfaces into a stagnant ambient dry air, unsaturated mixture of air and vapor and superheated vapor are shown in Figures (7-9). Figure(7) describes the behavior of water evaporation rate as a function of free stream temperature into the three environment of pure air, wet air, and superheated steam from a flat vertical plate (α = 0.0). The evaporation rate increases with temperature, however, the rate of evaporation is higher for dry air than for wet air and superheated steam until the inversion temperature (500°C) is reached when the rate into superheated steam becomes bigger. A similar trend is shown in Figure (8) for a wavy vertical surface ($\alpha = 0.2$). A comparison between the rates of evaporation for a flat and a wavy vertical surface is demonstrated in Figure (9). Under identical conditions the rate of evaporation as can be seen is higher for flat surfaces than wavy ones. However, the geometry of the surface has no effect on the value of the inversion temperature.

CONCLUSION

This paper presents a theoretical study of water evaporation from wetted vertical wavy surface. The mathematical model based on natural convection of combined mass and heat transfer is applied. Finite difference scheme is used to solve numerically the set of partial differential equations which describe the evaporation behavior. A simple coordinate transformation is adopted so that results for a vertical flat plate are obtained. These results are in good agreement with those published in the literature and this gave a good check on the accuracy of the model.

The results showed that the rate of evaporation from wetted wavy surfaces is much lower than that from vertical surfaces under identical conditions. Furthermore, rates of evaporation of water are higher in pure air than in superheated steam until the inversion temperature of about 500°C is reached. The amplitude of the wavy surface is found to have no effect on the inversion temperature.

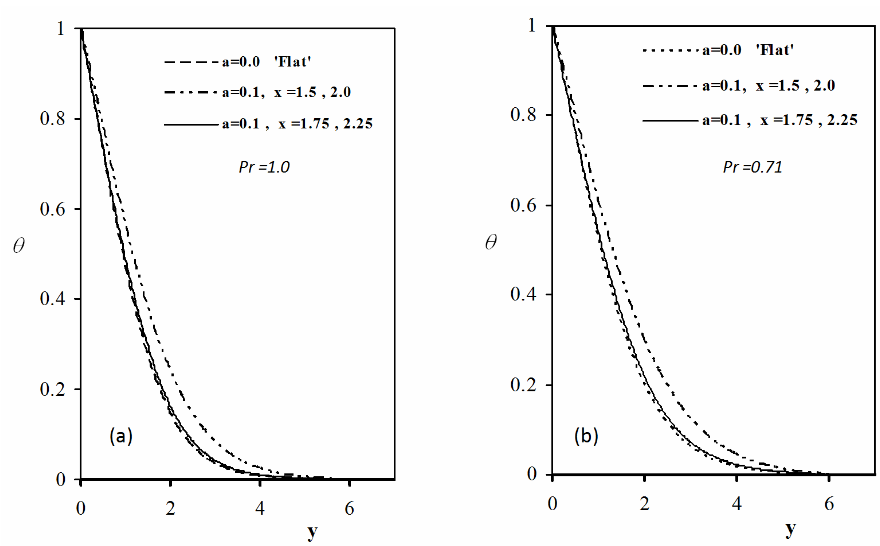

Figure 2: Temperature distribution (θ) for flat and wavy surface, (a) *Pr=1.0,* (b) *Pr=0.71*.

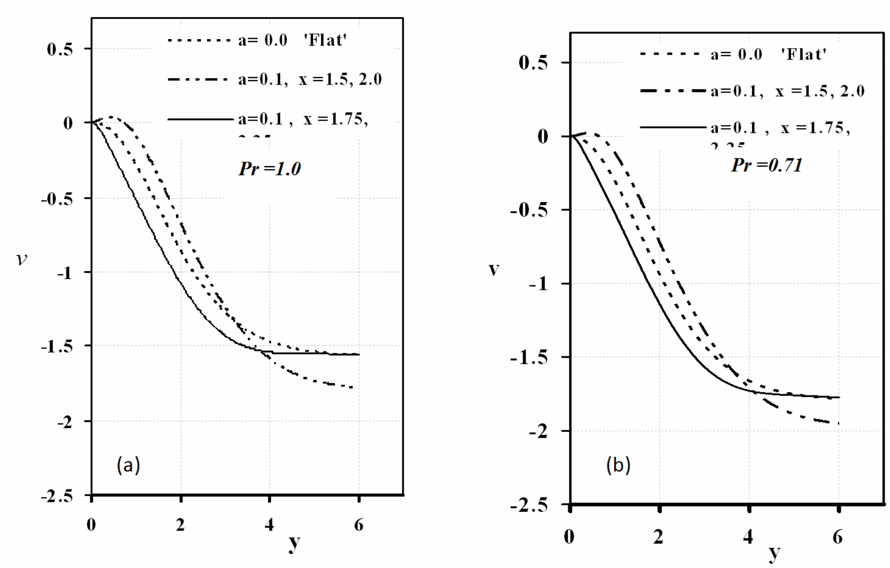

Figure 3: Normal velocity profiles (*v*) for flat and wavy surface, (a) Pr=1.0, (b) Pr=0.71.

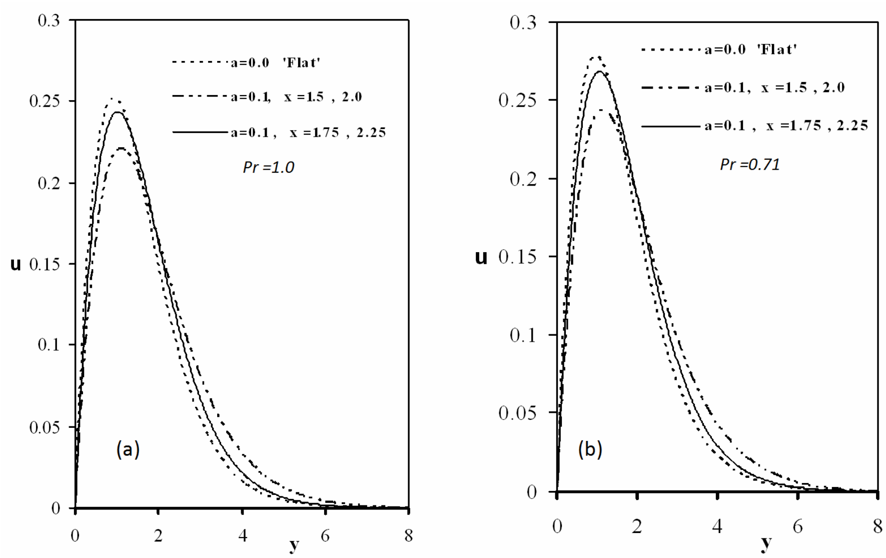

Figure 4: Axial velocity profiles (*u*) for flat and wavy surface; (a) *Pr=1.0*, (b) *Pr=0.71*.

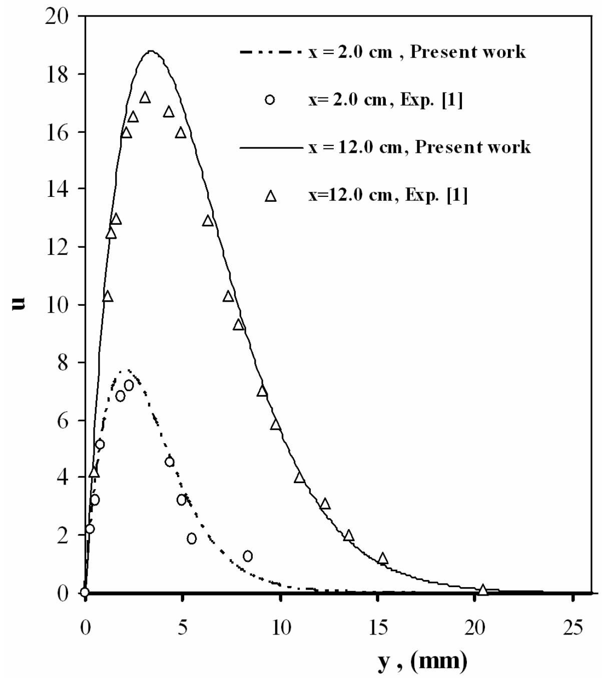

Figure 5: Dimensional Axial Velocity distribution (*u*) for vertical flat surface (α=0), at *x* = 2.0 cm and *x* = 12.0 cm

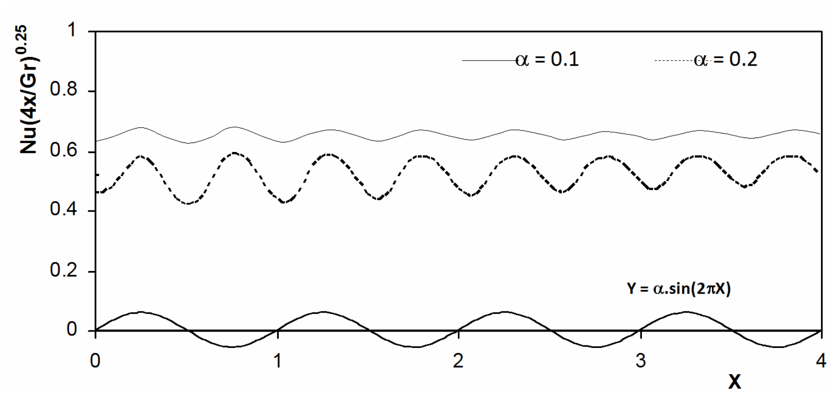

Figure 6: Local heat transfer rate for various amplitude wavelength ratios of wavy surfaces (α = 0.1, 0.2, at *Pr* = 1.0).

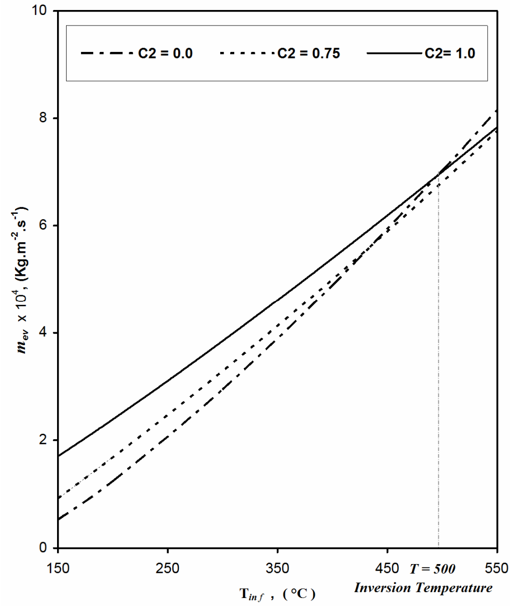

Figure 7: Evaporation rate of water from vertical flat surface (α = 0.0) into various of free stream mass fraction.

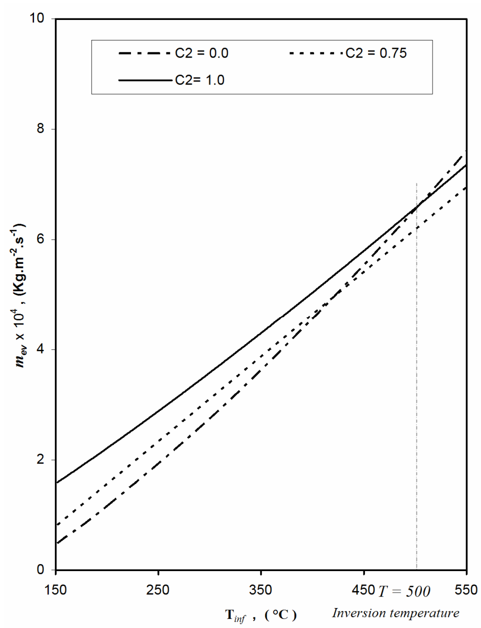

Figure 8: Evaporation rate of Water from vertical wavy surface (α = 0.2) into various of ambient mass fraction.

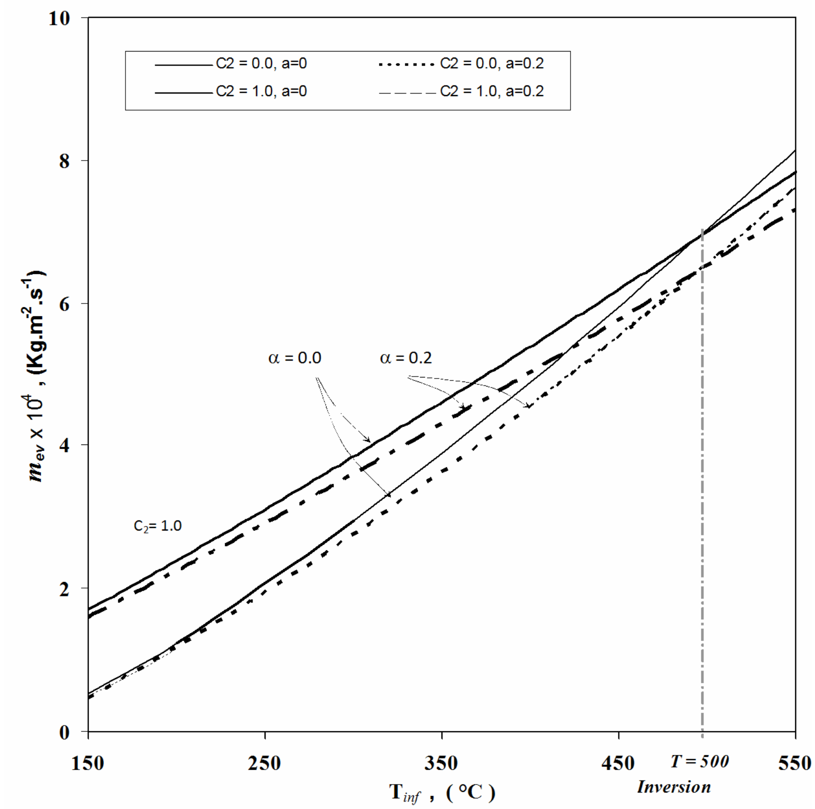

Figure 9: Evaporation rate of Water from vertical flat and wavy surfaces (α = 0.0, 0.2) in pure air and super heated vapor.

REFERENCES

[1] K. Brodowicz, An analysis of laminar free convection around isothermal vertical plate, International Journal of Heat and Mass Transfer, Volume 11, Issue 2, February (1968), pp. 201-204.

[2] F.A. Bottemanne, Theoretical solution of simultaneous heat and mass transfer by free convection about a vertical flat plate, Appl. Scient. Res. Volume 25, (1971), pp. 137–149.

[3] W. S. Fu and F. C. Duh, Combined heat and mass transfer in natural convection on a vertical flat plate, International Communications in Heat and Mass Transfer, Volume 15, Issue 2, (1988), pp. 179-191.

[4] J. Schenk, R. Altmann and J. P. A. De Wit, Interaction between heat and mass transfer in simultaneous natural convection about an isothermal vertical flat plate, Appl. Sci. Res. Volume 32, Dec (1976), pp. 599-606.

[5] L. S. Yao, Natural convection along a vertical wavy surface, Journal of heat transfer, Volume 105, Aug. (1983), pp. 465-468. 3

[6] Md. Mamun Molla, Md. Anwar Hossain and Lun Shin Yao, Natural convection flow along a vertical wavy surface with uniform surface temperature in presence of heat generation/absorption, International Journal of Thermal Sciences, Volume 43, (2004), pp. 157–163
[7] L. S. Yao, Natural convection along a vertical complex wavy surface, International Journal of Heat and Mass Transfer, Volume 49, (2006), pp. 281–286
[8] Jer-Huan Jang , Wei-Mon Yan, Hui-Chung Liu, Natural convection heat and mass transfer along a vertical wavy surface, International Journal of Heat and Mass Transfer, Volume 46, (2003), pp.1075-1083.
[9] S.U. Rahman, Natural convection along vertical wavy surfaces: an experimental study, Chemical Engineering Journal, Volume 84 (2001), pp. 587–591.
[10] S.U. Rahman and H. M. Badr, Natural Convection from a Vertical Wavy Surface Embedded in Saturated Porous Media, Ind. Eng. Chem. Res. Volume 41 (2002), pp. 4422-4429.
[11] J.C. Chu, A.M. Lane and D. Conklin, Evaporation of liquids into their superheated vapors, Ind. Eng. Chem. Volume 45, July (1953) pp.1586–1591.
[12] T. Yoshida, T. Hyodo, Evaporation of water in air, humid air and superheated steam, Ind. Eng. Chem. Process Design Develop. Volume 9, (1970), pp.207–214.
[13] L.C. Chow and J.N. Chung, Evaporation of water into a laminar stream of air and superheated steam, International Journal of Heat and Mass Transfer 26, (1983 a) 373-380.
[14] L.C. Chow and J.N. Chung, Water evaporation into a turbulent stream of air, humid air or superheated steam, in: Proceedings of the ASME National Heat Transfer Conference, ASME, No. 83-HT-2, New York, (1983 b).
[15] M. Hasan, A. S. Mujumdar and M. Altaleb, Laminar evaporation from flat surfaces into unsaturated and superheated solvent vapor. Drying'86, Volume II, (1986), pp.604-616.
[16] M. Haji, L.C. Chow, Experimental measurement of water evaporation rates into air and superheated steam, Journal of Heat Transfer, Volume 4 (1988), pp.185-192.
[17] R. Sheikholeslami and A. P. Watkinson, Rate of evaporation of water into superheated steam and humidified air, International Journal of Heat and Mass Transfer, Volume 35, Issue 7, July (1992), pp.1743-1751.
[18] J.P. Schwartze and S. Brocker, The evaporation of water into air of different humidities and the inversion temperature phenomenon, International Journal of Heat and Mass Transfer, Volume 43 (2000), pp.1791-1800.
[19] J.P. Schwartze and S. Brocker, A theoretical explanation for the inversion temperature, Chemical Engineering Journal, Volume 86 (2002), pp. 61-67.
[20] E.P. Volchkov, A.I. Leontiev and S.N. Makarova, Finding the inversion temperature for water evaporation into an air-steam mixture ,International Journal of Heat and Mass Transfer, Volume 50, Issues 11-12, June (2007), pp. 2101-2106
[21] G. M. Harpole, Droplet evaporation in high temperature environment, Trans. ASME, Journal of heat transfer, Volume 103, Feb. (1981), pp. 86 - 91.
[22] Dale A. Anderson, John C., Richard H., Computational fluid mechanics and heat transfer, McGraw-Hill, 1984.
[23] Suhas V. Patankar, Numerical Heat Transfer and Fluid Flow, McGraw-Hill, 1980

NOMENCLATURES

a	amplitude of the wave surface, (m)
C	mass fraction of the diffusing component (Air).
D	binary diffusion coefficient, [m^2/sec].
g	gravitational acceleration, (m/sec^2).
Gr	Thermal Grashof number.
$Gr_{,c}$	Grashof number for mass diffusion.
h_{fg}	Latent heat of vaporization, (W.sec/kg or J/kg).
L	Wave length, (1.0 m).
k	Thermal conductivity, (W/m.°C).
n	Normal victor.
Nu	Nusselt number.
$\overline{\dot{m}}_{ev}$	Average of evaporation rate, (kg/m^2.sec)
M	Molecular weight, (g/mol)
P	Atmospheric pressure, (1 atm).
P_{vs}	Vapor pressure, (atm).
Pr	Prandtl number.
R	Ratio of Grashof numbers (buoyancy ratio).
t	Tangent victor.
S	distance measured along the wavy surface from the leading edge , (m)
Sc	Schmidt number.
Sh	Sherwood number.
T	Temperature [°C].
u, v	Axial and normal velocity, (m/sec).
x, y	Vertical and horizontal coordinates.

Greek symbols

α	Dimensionless amplitude of the wave ratio = a/L.
β	Volumetric coefficient of thermal expansion.
B^*	Volumetric coefficient of expansion with mass fraction,
v	Kinamatic viscocity, (m^2/sec).
μ	Dynamic viscosity of the fluid (kg/m.sec)
ρ	Density of the fluid (kg/m^3)

Superscripts

‾	Dimensional quantity.
^	Dimensionless quantity.
′	Derivation with respect to *x*.

Subscripts

1	Evaporated substance.
2	Diffusing component (air)
w	condition at the surface (wall).
∞	condition at the free stream.