EVAPORATION OF BENZENE AND METHANOL FROM WETTED VERTICAL WAVY SURFACE INTO A STAGNANT AMBIENT

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الملخص

يقدم هذا البحث دراسة نظرية لعملية تبخير البنزين والميثانول بطريقة الحمل الحراري الطبيعي (الحر) من سطح متموج مبلل بالبنزين والميثانول وعند درجة حرارة ثابتة وتركيز ثابت إلى وسط راكد مكون من الهواء الجاف أو مخاليط مختلفة من الهواء النقي ومن بخار البنزين والميثانول ومن البخار المحمص للبنزين وللميثانول.

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

النتائج أثبتت أن تموج الأسطح له تأثير على معدل التبخر حيث يتناقص المعدل بزيادة سعة الموجة ولم يكن لها أي تأثير على درجة الانقلاب. كما أن معدل تبخر البنزين والميثانول يزداد بزيادة درجة حرارة الوسط. معدل التبخر عند استخدام الهواء الجاف أعلى من معدل التبخر عند استخدام البخار المحمص إلى عند درجة حرارة الانقلاب وبعدها يصبح معدل التبخر باستخدام البخار المحمص هو الأعلى.

ABSTRACT

This work presents a theoretical study of the evaporation of two solvents, namely; benzene and methanol, from their wet vertical wavy stationary surfaces in stagnant ambient of pure air, unsaturated mixtures of air and vapors and superheated 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 flat plate. A marching finite-difference scheme is used for the analysis. The effect of the amplitude of the wavy surface on the evaporation rate and the inversion temperature, as well as the effect of ambient temperature and free stream composition are studied.

The results demonstrate that for wavy surface, the evaporation rate is significantly lower than that for a flat surface under identical conditions. The evaporation rate of the solvent increases by increasing the ambient temperature and it is higher in pure air than that in superheated vapor up to the inversion temperature. Above this temperature the evaporation rate of each solvent is higher in superheated steam than in pure air. The amplitude of the wavy surface has no effect on the inversion temperature.

KEYWORDS: Evaporation; Heat transfer; Inversion Temperature; Mass Transfer; Mathematical Modeling; Natural (Free) Convection; Wavy Surface

INTRODUCTION

The evaporation by natural convection of heat and mass transfer find several applications in drying processes of wet materials from surfaces which mostly irregular surfaces. The natural convection has been one of the most important research topics in heat transfer. Convective flow driven by temperature difference about regular surfaces have been studied extensively in the past [1-4].The natural convection about a heated vertical wavy surface has received a great deal of attention due to its relation to practical applications of complex geometries. Many authors studied the natural convection heat as well as combined heat and mass transfer over a vertical wavy surface [5-10].

The characteristics of natural convection heat and mass transfer from regular surfaces are relatively important in many chemical engineering processes. The evaporation of liquids into their own vapor, air and mixtures thereof is a problem of coupled heat and mass transfer, where the subject of evaporation of water into an air stream has received considerable attention. Superheated steam has also been recommended as an attractive drying medium for materials that are not temperature sensitive.

Chu et al. [11] investigated experimentally the evaporation of three liquids; water, 1-butanol and benzene into their superheated vapors. Yoshida and Hyodo [12] carried out extensive experiments used a wetted wall column with countercurrent water and air. They were the first to find an inversion temperature which was slightly affected by the mass flow rate of the drying agent. The steady state evaporation of water into a laminar stream of air, humid air and superheated steam have been investigated numerically by Chow and Chung [13], they found the inversion temperature about 250ºC. For the same mass flux of the free stream and at low free stream temperatures, water evaporates faster in air than in humid air and in superheated steam, the trend was reversed at high free stream temperatures. Chow and Chung [14] extended the analysis for water evaporation into a turbulent stream of air, humid air and superheated steam. Their results showed that for a turbulent flow condition of the free stream, inversion temperature was approximately 190ºC, which was 60ºC lower than the laminar flow situation.

Hasan et al. [15] carried out a numerical study of laminar evaporation from horizontal flat surfaces into unsaturated and superheated solvent vapor, where the laminar boundary layer evaporation of water, benzene and methanol from their moving wet surfaces into co-current streams of pure air, unsaturated mixtures of air and vapors, and superheated vapors were compared. For the air-water pair, their results confirm the results of Chow and Chung [14] that, for the same mass flux of the free stream, water evaporated more rapidly in air than in humid air at low free stream temperature; the reverse was true at high free stream temperature. For the water-air system, the inversion temperature was found to be near 260ºC.

Schwartze and Brocker [16] investigated a theoretical study of the evaporation of water into air of different humidity and the inversion temperature phenomenon. They assumed that heat is transferred from the gas to the liquid only by convection and that there is no heat flux between wall and liquid. Furthermore, the liquid phase was assumed to be at the temperature of evaporation,

Maria et al. [17] presented a theoretical model describes the transport phenomena occurring during food drying process. The agreement between experimental results reported in the literature and theoretical predictions of their model was rather good.

Evaporation of water and some other materials into a moving stream of air or superheated vapor from regular surfaces by forced convection has been studied rather extensively. In contrast, the evaporation associated with free-convective thermal and mass transfer from wetted stationary vertical wavy surface to a stagnant medium seems not has been well investigated. Esalah and said [18] studied the effects of evaporation surface geometry and the ambient conditions; air, unsaturated air and superheated vapor, on the evaporation rate of water and on the inversion temperature phenomenon when free convection is considered. In the present work, the effects of the amplitude of the sinusoidal wavy surface, and the evaporation ambient conditions on the evaporation rate of benzene and methanol and on their inversion temperatures are investigated.

The sinusoidal wavy surface is used as an example; because it can be considered as an approximation to much practical geometry for which natural convention evaporation is of interest. The transformation method proposed by Yao [5] is used to transform the sinusoidal wavy surface into a flat surface. A numerical technique is used to solve the governing equations of this problem. The momentum, energy and mass equations are solved simultaneously using a finite-difference scheme. The results were compared with experimental data presented by Brodowicz [1] for natural convection about vertical flat surface and with numerical results presented by Yao [7] for natural convection about vertical wavy surface; The results are also compared with those given by Bottemanne [2] for vertical flat surface.

PROBLEM FORMULATION

In this work, the transformation method proposed by Yao [1], is used to transform a sinusoidal wavy surface into a flat surface. The problem involves a natural convection on a semi-infinite isothermal vertical wavy plate with a temperature and mass fraction different from that of the ambient as shown in Figure (1).

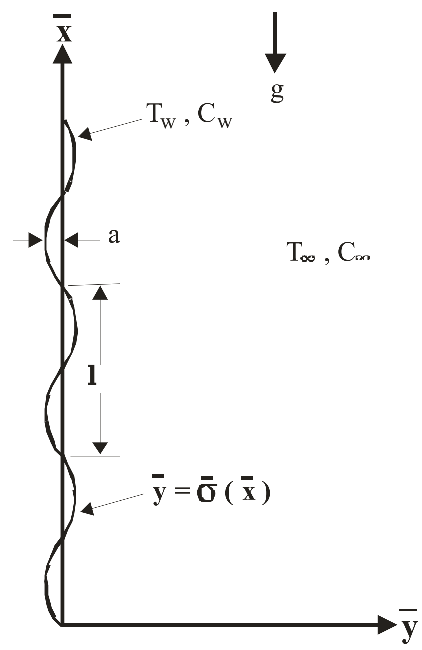


Figure 1: Schematic diagram of the physical system

The thermo-physical properties are assumed to be constant except for density variations in the buoyancy term in the x-momentum equation. The Boussinesq approximation is used to characterize the buoyancy effect.
The surface of the plate is described by;

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

Where $\bar{\sigma}$ is a function describing the surface geometry. For a sinusoidal wavy surface, $\bar{\sigma} = a \sin(2\pi \bar{x})$, where a is the amplitude of wavy surface.

The plate is situated in an otherwise quiescent fluid with a temperature T_∞ and mass fraction C_∞. The plate is maintained at constant temperature T_w, and constant mass fraction C_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 normal to the x-coordinate

Steady state evaporation of benzene and methanol into a stagnant air, unsaturated air or superheated vapor is considered. This stagnant fluid is at temperature T_∞ and the mass fraction of the diffusing component is c_∞. 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 free stream itself.

The dimensional governing equations are the continuity, the Navier- Stockes equations, the energy equation and the species equation in two-dimensional Cartesian coordinates $(\bar{x}, \bar{y})$. 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 [18]. The governing equations are then transformed using the parameters proposed by Yao[5] and reduced to the following four dimensionless equations. For details, the reader is referred to references [5, 18].

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

$$(4x)u\frac{\partial u}{\partial x} + (v - yu)\frac{\partial u}{\partial y} + (2 + \frac{4x\sigma'\sigma''}{1+\sigma'^2})u^2 = \frac{(\theta + R\psi)}{1+\sigma'^2} + (1+\sigma'^2)\frac{\partial^2 u}{\partial y^2} \tag{3}$$

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

$$(4x)u\frac{\partial \psi}{\partial x} + (v - yu)\frac{\partial \psi}{\partial y} = \frac{1+\sigma'^2}{Sc}\frac{\partial^2 \psi}{\partial y^2} \tag{5}$$

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 neither 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:

$$v\big|_w = (1+\sigma'^2)^{\frac{1}{2}} \frac{\overline{w}_n\big|_w}{(\frac{\beta g \Delta T v^2}{4\overline{x}})^{\frac{1}{4}}} \tag{6}$$

The case when the ambient is a Superheated Vapor.

The governing equations describing this problem are equations (29–31) 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

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

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

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:

$$c(x,0) = c_1 = \frac{M_v/M_a}{P/P_{vs} + M_v/M_a - 1} \tag{7}$$

Where; P_{vs} is a vapor pressure.

at the free stream: y → ∞

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

- 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 $\quad u = 0$ $\quad\theta = 1$

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

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 → ∞

u → 0 $\quad$ θ → 0

Evaporation rate

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

$$\begin{aligned} \overline{\dot{m}}_{ev} &= \frac{1}{s}\int_0^x \dot{m}(x)ds = \frac{\rho}{s}\int_0^x \dot{v}(x)ds \\ &= \frac{\rho}{s}\int_0^x \dot{v}(x)(1+\sigma'^2)^{1/2}dx \end{aligned} \tag{8}$$

$$\overline{m}_{ev} = \frac{Gr^{1/4}.K}{h_{fg}}\left(T_w - T_\infty\right)\frac{1}{s}\int_0^x \left[\frac{\left(1+\sigma'^2\right)}{\left(4x\right)^{1/4}}\frac{\partial\theta}{\partial y}\right]_{y=0} dx \tag{9}$$

Where: $$s = \int_0^x \left(1 + \sigma'^2\right)^{1/2} dx \tag{10}$$

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.

Since 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:

$$T_r = T_w + r\left(T_\infty + T_w\right) \tag{11}$$

$$C_r = C_w + r\left(C_\infty + C_w\right) \tag{12}$$

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 [14]. For benzene-air and methanol-air systems, the properties correlations given in reference [15] are used in this work.

Numerical method and computational procedure

If we consider the case when the evaporation is into an unsaturated air, then the governing equations are the equations (2-5). The energy equation and the species equation (eqs. (4-5)) are liner in θ and ψ, respectively. The momentum equation (eq. (3)), 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 is the Newton-Raphson method [19-20]. The procedure for linearizing the nonlinear terms of the momentum equation demands that.

$$u.u_x = -u^*.u_x^* + u^*.u_x + u.u_x^*$$

$$u.u_y = -u^*.u_y^* + u^*.u_y + u.u_y^*$$

$$u^2 = 2.u.u^* - u^{*2}$$

Where the star ‘*’ means previous iteration of the respective variable

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:

$$\frac{\partial u}{\partial x} = \left(\frac{u_{i,j} - u_{i-1,j}}{\Delta x} \right) \quad and \quad \frac{\partial u}{\partial y} = \left(\frac{u_{i,j+1} - u_{i,j}}{\Delta y} \right)$$

The governing equations are transformed into the finite-difference form and written in the form algebraic equations:

$$a_j.F_{i,j} + b_j.F_{i,j+1} + c_j.F_{i,j-1} = d_j$$

Where; F represents u , θ or ψ.

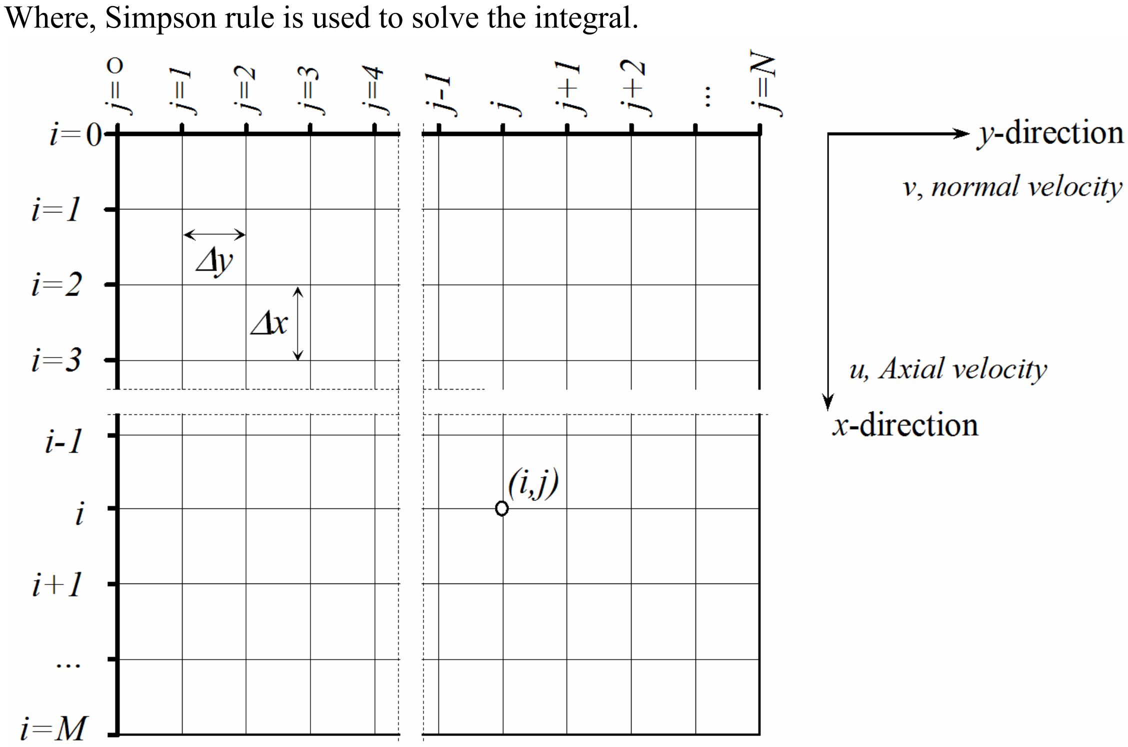
The solution of the obtained algebraic equations was marched in downstream direction since flow under consideration is a boundary layer type. Each of the finite difference equations forms a tridiagonal matrix equation, which can be efficiently solved by using the well known tridiagonal matrix algorithm (TDMA).

The x-grid size and the y-grid size were fixed at 0.025, and at 0.02, respectively. finite difference grid is shown below.The singularity at x = 0, has been removed by scaling. The computation is 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}.

The evaporation rate is calculated using Equation (9), which is written in finite-difference form as:

$$\overline{\dot{m}}_{ev} = \frac{Gr^{1/4}k}{h_{fg}} (T_w - T_\infty).\frac{1}{s} \int_0^x \frac{\left(1+\sigma_i'^2\right)}{\left(4x_i\right)^{1/4}}.\left(\frac{-\theta_{i,j+2} + 4\theta_{i,j} - 3\theta_{i,j}}{2\Delta y} \right) dx$$

Where, Simpson rule is used to solve the integral.



The finite difference grid

RESULTS AND DISCUSSIONS

The numerical resu1ts are obtained for the wavy surface which described by $\sigma(x)=\alpha.\sin(2\pi x)$ in dimensionless form, for various of dimensionless amplitude (α), to study the geometric effect on the natural convection of heat and mass transfer for ambient at different conditions.

The first results which are obtained for the limiting case of natural convection heat transfer from wavy surface, are compared with Brodovic's [1] Bottemanne's [2] and Yao's [5] results and presented in a previous related work[18].

The dimensionless local heat transfer rates for the wavy surface of (α=0.1) and (α=0.2) are shown in Figure (2). From this Figure it is obvious that increasing the amplitude of wavy surface tend to increase the amplitude of the local heat transfer rate and the wavelength of local heat transfer rate is half of that of wavy surface. For the position of the wavy surface parallel to the gravitational force at crest and trough, the velocity is large and so is the local heat transfer rate. Also, the local heat transfer rate is decrease with increase of vertical distance (x).

Then the results for evaporation rate of benzene and methanol from their wetted stationary wavy surfaces into a stagnant ambient of pure air, unsaturated mixtures of air and vapors and superheated vapors are presented in Figures (3-8) . The figures show the effect of geometry on the evaporation rate of benzene and methanol into stagnant ambient of air mixture with various mass fraction ($C_{2,\infty}$ = 0.0, 0.5 and 1.0) within the temperature range of free stream (100-250ºC) for benzene-air system, Figure (2), and range of (150-300ºC) for methanol-air system, Figure (7). These Figures show that at the lower temperatures of ambient the evaporation rates are greater in air than in unsaturated vapor and superheated vapor. This trend is reversed at higher free stream temperatures, where the intersection point of the curves of evaporation rates for superheated vapor and pure air is called the inversion temperature. For benzene-air system this temperature is approximately at 207 ºC, which is the same for flat and wavy surface as shown in Figure (6). Similar behavior to that of the experimental study of Chu et al. [12], for evaporation of benzene from flat surface was observed.

The inversion temperature of methanol-air system is approximately at 285ºC, which is the same for flat and wavy surface as shown in Figure (8).

Figures (5) and (8) show that the evaporation rates of benzene and methanol are higher from vertical flat plate than that from vertical sinusoidal wavy surface, for the same evaporation surface and for the same ambient conditions.

The average evaporation rate of Benzene from vertical flat surface (α=0.0) and wavy surface (α = 0.2) are presented in Figure (9). The average evaporation rate from flat surface is greater than that from wavy surface. This may be attributed to the thickness of the diffusion boundary layer which it is thicker in wavy surface than that in flat surface. The highest evaporation rate is close o the leading edge and then decreases and gradually levels off as the axial coordinate (x) increase.

CONCLUSIONS

This paper presented a mathematical model and computer program to simulate heat and mass transfer for evaporation of benzene and methanol from wetted vertical wavy surface, as well as flat surface performed. The governing equations allowing for free convection effects are solved numerically using finite difference scheme.

The results demonstrate that, for evaporating of wet wavy surface, the evaporation rate is significantly lower than that for a flat surface under identical conditions. The results also show that for benzene- air system, the evaporation rate is higher in pure air at free stream temperatures below 207°C, and the reverse is true for the temperature above 207°C.

For methanol-air system, it is found that the evaporation rates of methanol are highest in pure air than that in superheated vapor; this result was reversed above the free stream temperature of 285°C, which defined as inversion temperature. The amplitude of wavy surface is found have no effect on the inversion temperature, un1ike the rate.

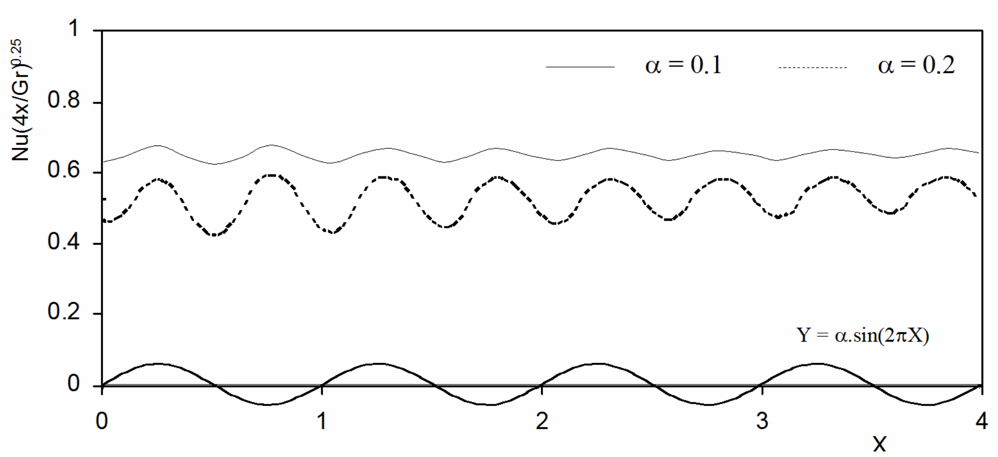


Figure 2: Local Heat transfer rate for various amplitude wavelength ratio of wavy surfaces (α = 0.1, α = 0.2, at *Pr* = 1.0).

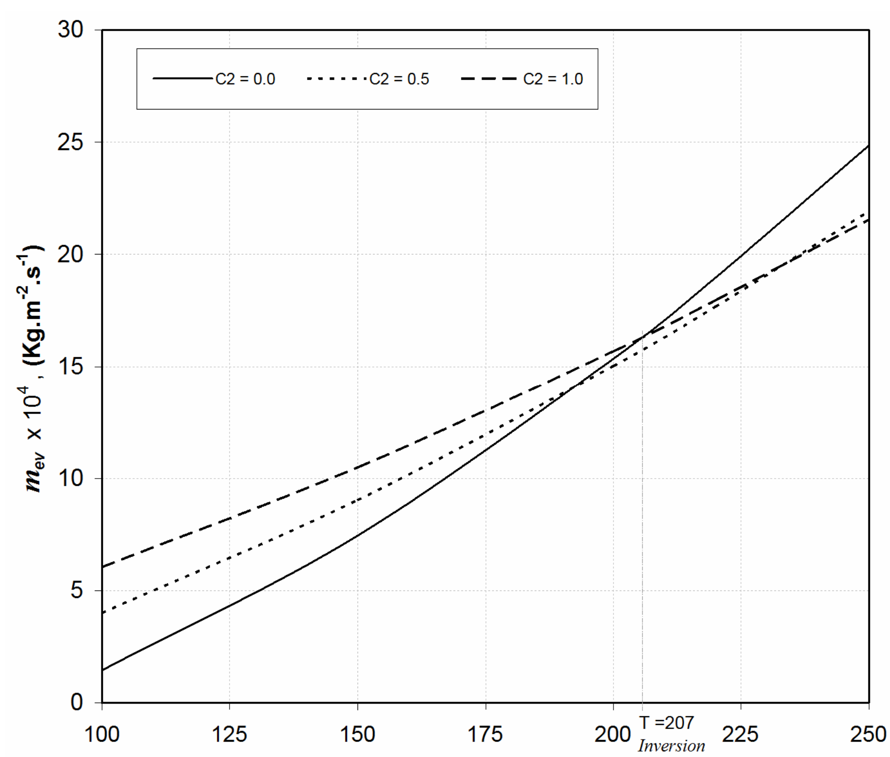


Figure 3: Evaporation rate of Benzene from vertical flat surface (α = 0.0)

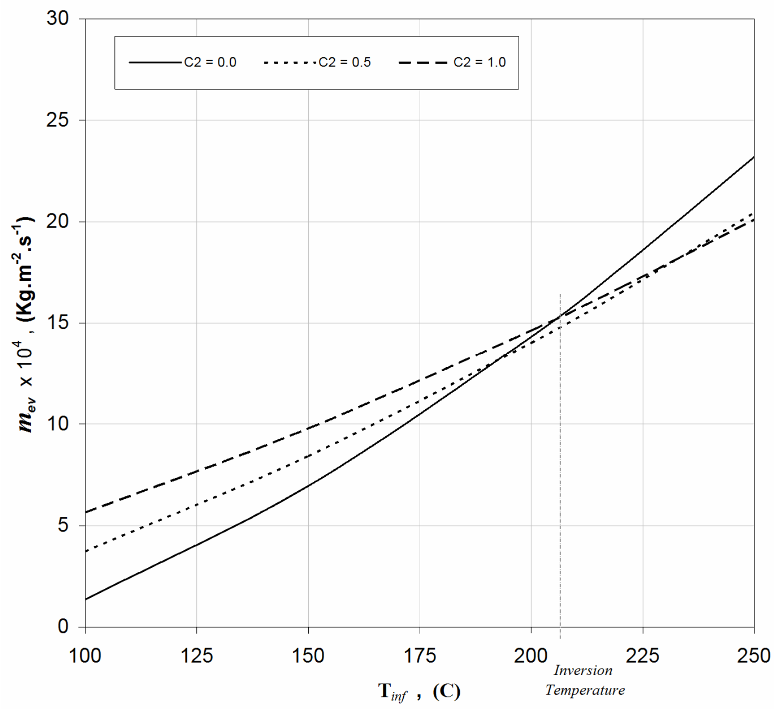


Figure 4: Evaporation rate of Benzene from vertical wavy surface (α = 0.2) in to various of free stream mass fraction.

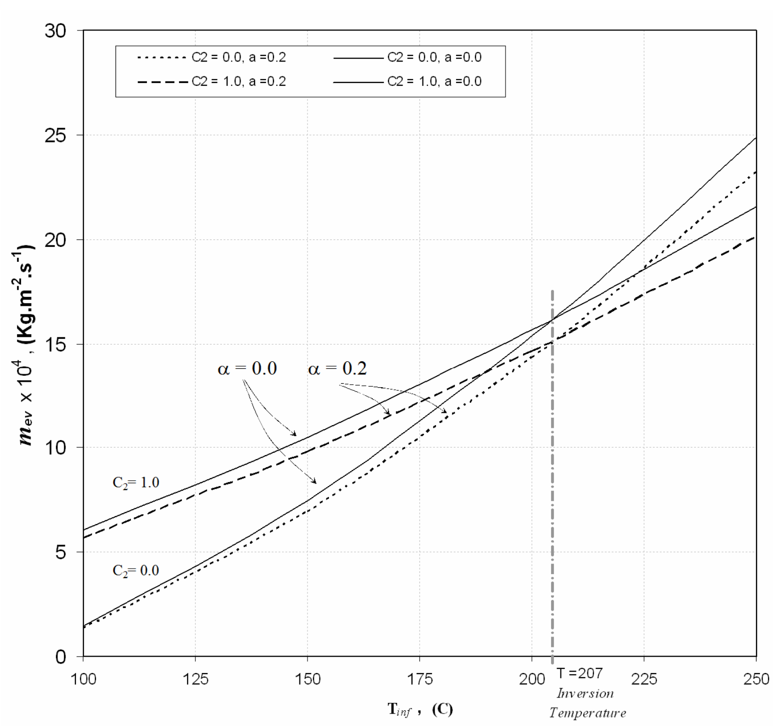


Figure 5: Evaporation rate of Benzene from vertical flat and wavy surfaces (α = 0.0, α = 0.2) in pure air and super heated vapor.

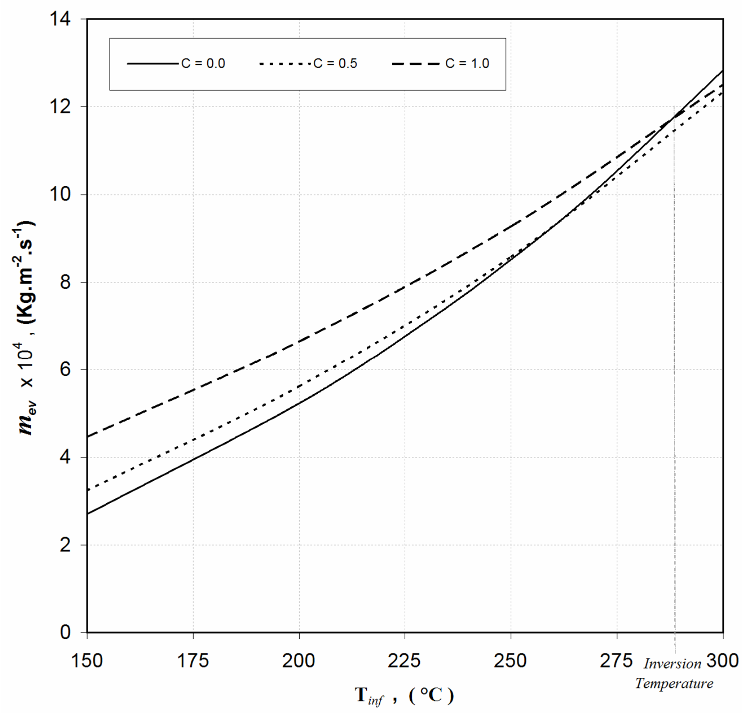


Figure 6: Evaporation rate of Methanol from vertical flat surface (α = 0.0) in to various of free stream mass fraction.

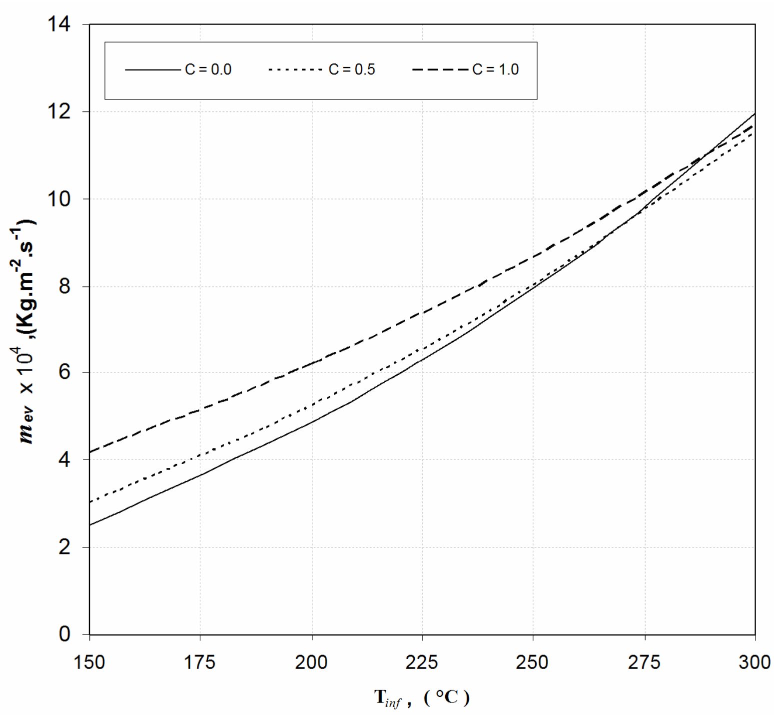


Figure 7: Evaporation rate of Methanol from vertical wavy surface (α =0.2)

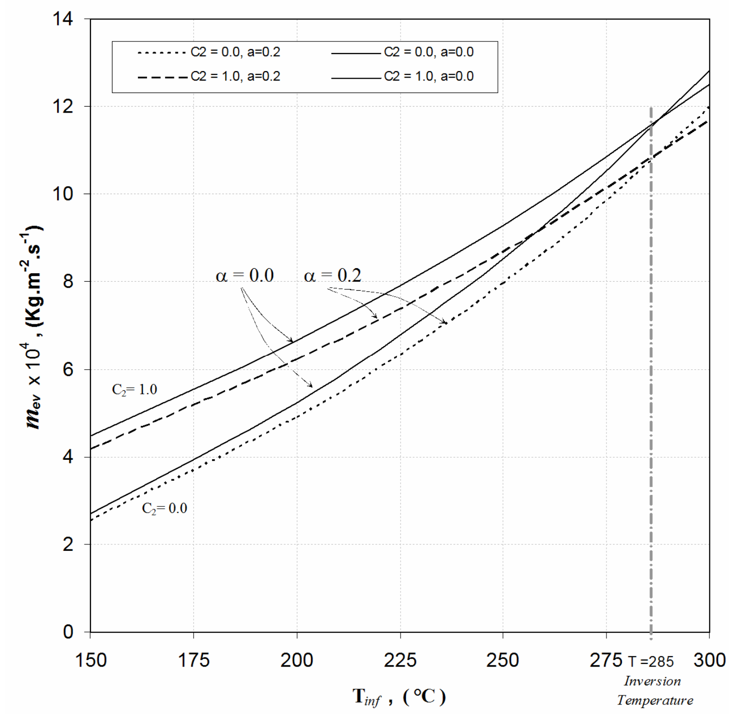


Figure 8: Evaporation rate of Methanol from vertical flat and wavy surfaces ($\alpha = 0.0$, $\alpha = 0.2$) in pure air and super heated vapor.

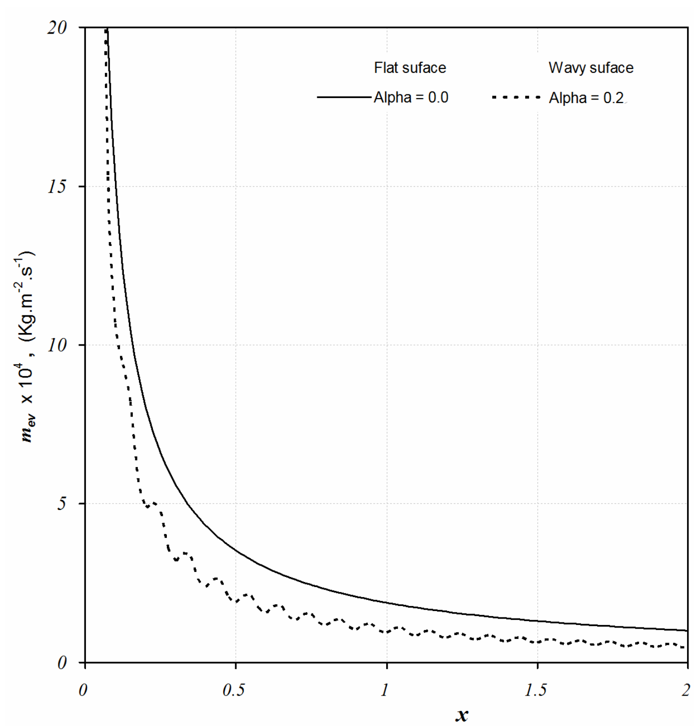


Figure 9: Averaged Evaporation rate of Benzene from vertical flat and wavy surfaces ($\alpha = 0.0$, $\alpha = 0.2$) at $T_\infty = 100$ ºC, Pr = 0.74, Sc = 0.26.

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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	Dimesionless axial and normal velocity
x, y	dimesionless vertical and horizontal coordinates

Greek symbols

α	Dimensionless amplitude of the wave ratio = a/L
β	Volumetric coefficient of thermal expansion
β	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

$'$	Derivative with respect to x

Subscripts

$_1$	Evaporated substance
$_2$	Diffusing component (air)
w	Condition at the surface (wall)
∞	Condition at the free stream