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Heat Transfer and Fluid Flow in Falling Film of Vertical Tube Evaporation: A Numerical Solution.

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انتقال الحرارة والمائع خلال طبقة رقيقة من السائل يحدث بها تبخير وتتحرك الى أسفل داخل أنبوب فى وضع رأسى .... الحل الحسابى

"HEAT TRANSFER AND FLUID FLOW IN FALLING FILM OF VERTICAL TUBE EVAPORATION: A NUMERICAL SOLUTION"

By
محمد على درويش ، شاجم الناجم ، عوض أحمد الحادق
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ملخص البحث :

يهتم هذا البحث بدراسة انتقال الحرارة والمائع خلال طبقة رقيقة من السائل يحدث بهنا تبخير وتتحرك الى أسفل داخل أنبوب فى وضع رأسى حسابيا . استخدمت طريقة الفروق المحددة مع التكرار فى هذه الدراسة كما أخذ فى الاعتبار أن السريان من النوع الاضطرابى وثنائى الاحداثيات الاسطوانية وأيضا مستقر . معادلات السريان والطاقة صيغت بطريقة الفروق المحددة وتم استخدام الحاسب الالى مع استخدام الطريقة المتكررة لجار ـ سيدال للوصول الى قيم دقيقة ومقبولة . السرعة ودرجة الحرارة تم حسابتها بالطريقة السابقة ومن ثم تم حساب تعامل انتقال الحرارة بين المائع وسطح جدار الانبوب . كما تمت مقارنة النتائج مع آخرين تم الحصول عليها سابقا ووجدت النتائج الحديثة فى اتفاق جيد معهم .

ABSTRACT:

The present work studies the heat transfer and fluid flow in a falling film of vertical tube evaporators numerically. A finite difference technique, with iterative method, has been applied in these solutions.

The flow is considered turbulent, cylindrical coordinates, and steady. Momentum, and energy equations are formulated in finite difference technique and computations are performed, utilizing Gauss-Seidal point iterative method to obtain an acceptable accuracy. Velocity developed and temperature distributions in a falling film have been obtained, and the heat transfer coefficient is calculated. The results have been compared with those obtained by others and a good agreement has been found.

NOMENCLATURE:

A	Proportionality constant in eddy diffusivity expression, dimensionless	
c_p	Specific heat capacity	J/kg K
g	Gravity acceleration	m/s^2
h	Heat transfer coefficient	W/m^2K
I	Increment in nodes in x-direction	
J	Increment in nodes in y-direction	
K	Thermal conductivity	W/mK
k	Constant in equation (8)	
m	Number of nodes in x-direction	
n	Number of nodes in y-direction	
P	Pressure	N/m^2

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T	Temperature	K
q_w	Heat flux	W/m^2
T^+	Dimensionless temperature	
u	Velocity in the film in x-direction	m/s
u^*	Friction velocity	m/s
u^+	Dimensionless velocity (u/u^*)	
v	Velocity in the film in y-direction	m/s
V	Vapour velocity	m/s
X	Distance in flow direction	m
Y	Distance perpendicular on the flow direction	m
Y^+	Dimensionless distance, (yu^*/γ)	
α	Thermal diffusivity	m^2/s
Γ	Mass flow rate per unit perimeter	kg/m.s
δ	Film thickness	m
δ^+	Dimensionless film thickness	
ε_M	Eddy diffusivity for momentum	m^2/s
ε_H	Eddy diffusivity for heat	m^2/s
ε^+	Dimensionless eddy diffusivity $(1 + \frac{\varepsilon_M}{\gamma})$	
μ	Dynamic viscosity	kg/m.s
γ	Kinematic viscosity	m^2/s
ρ	Density	kg/m^3
σ	Surface tension	N/m
τ	Shear stress	N/m^2
τ_v	Shear stress at the liquid/vapour interface	N/m^2
τ_w	Shear stress at the wall	N/m^2
τ^+	Dimensionless shear stress	

Dimensionless number

$$Ka = \left(\frac{\mu^4 g}{\rho^3}\right)$$ Kapitza number

$$Pr = \left(\frac{C_p\ \mu}{K}\right)$$ Prandtl number

$$Pr_t = \left(\frac{\varepsilon_M}{\varepsilon_H}\right)$$ Turbulent Prandtl number

$$Re_L = \left(\frac{4\ \Gamma}{\mu}\right)$$ Film Reynolds number

$$Re_v = \left(\frac{dV\rho}{\mu}\right)$$ Vapour Reynolds number

Subscripts:

v = Vapour
i = Inlets interface
L = Liquid
t = Turbulent
W = Wall
X = Local value
o = Outlet
Crit = The value approaches its transition (or critical) limit

INTRODUCTION:

Heat transfer through falling-film or spray-film evaporation has been widely employed in heat exchange devices in the chemical, refrigeration, petroleum refining, desalination and the food industries.

It is apparent that there is a trend in the last two decades, favouring vertical tube evaporation (VTE) over multistage flash (MSF), as indicated by recent competitive bids for large desalination plants.

Modelling of turbulent liquid films has been the target of extensive research spanning the last seven decades. Detailed understanding of the film transport processes was of paramount importance for evaluating the performance of various heat-exchanger configurations.

Nusselt (1916) solved the momentum and energy equations for smooth laminar freely-falling liquid films by neglecting the effects of interfacial waves or vapour shear stress. The importance of surface waves on the transport processes in laminar films has been stressed by several investigators. The works by Benjamin (1957), Hankatty and Hershman (1961), Whitakar (1964), Kapitza (1965), Massot et al. (1966), Gollan and Sideman (1969) and Berbente & Ruckenstein (1968) are only a few examples. Theoretical models by these authors led to lower estimates of the film thickness compared to Nusselt's solution. It is interesting to note that many of these analyses define the wave characteristics as functions of the Reynolds and additional dimensionless parameters, namely the Kapitza number (Ka). Recently Al-Najem et al (1992) formulated a general analytical solution for evaporation turbulent falling films and developed a correlation of local heat tansfer coefficient along the tube length.

Turbulence Model:

Turbulent film flow is a highly complicated phenomenon. Turbulence models developed for highly-turbulent flows should be modified to account for changes in wave activity associated with transition from wavy-laminer to turbulent-film flow. This goal can be achieved through empirical correlations which account for the Kapitza number (Ka).

In a gravity-driven film, the velocity u, and temperature T, at a distance y from the solid wall (see Figure 1) are obtained from the momentum equation and the heat flux distribution across the film:

$$1-\frac{y^+}{\delta^+} = \left(1+\frac{\varepsilon_\mu}{\gamma}\right)\frac{du^+}{dy^+} \qquad [1]$$

and

$$\frac{q}{q_w} = \frac{1}{P_r}\left(1+\frac{P_r}{P_{rt}}\right).\frac{\varepsilon_M}{\gamma}\frac{\partial T^+}{\partial y^+} \qquad [2]$$

where ε_M/γ is the eddy-to-kinematic viscosity ratio, Pr and Pr_t are the Prandtl number and the turbulent Prandtl number, q and q_w are the local heat flux normal to the wall and the wall flux, respectively.

The variables of [1] and [2] are non-dimensionlized in terms of the friction velocity u_* as follows:

$$u^* = \sqrt{\frac{\tau_w}{\rho}} = \sqrt{g\delta}, \qquad [3]$$

$$y^+ = \frac{u^* y}{\gamma}, \qquad [4]$$

$$u^+ = \frac{u}{u^*}, \qquad [5]$$

$$\delta^+ = \frac{u^*\delta}{\gamma}, \qquad [6]$$

and

$$T^+ = \rho C_p u^* \frac{(T_w - T)}{q_w}, \qquad [7]$$

Most of the effort in modelling turbulent liquid films centers on the determination of the eddy-viscosity profile across the film. Mudawwar and El-Masri (1986) have defined the eddy viscosity as follows:

$$\frac{\varepsilon_M}{\gamma} = -\frac{1}{2} + \frac{1}{2}\sqrt{1+4k^2y^{+2}\left(1-\frac{y^+}{\delta^+}\right)\left[1-\exp\left\{-\frac{y^+}{A}\right.\right.}$$

$$(1-\frac{y^+}{\delta^+})^{1/2} * (1-\frac{0.865\ Re^{1/2}crit}{\delta^+})\}]^2$$

$$0 < y^+ < \delta^+ \qquad [8]$$

where:

$$\text{Heating: } Re_{crit} = \frac{97}{Ka^{0.1}} \qquad [9]$$

$$\text{Evaporation: } Re_{crit} = \frac{0.04}{Ka^{0.37}} \qquad [10]$$

The Pr_t profile is correlated from experimental data of Ueda et al (1977):

$$Pr_t = 1.4\ Exp\ (-15\ \frac{y^+}{\delta^+}) + 0.66, \qquad (11)$$

$$k = 0.40, \qquad [12]$$

and

$$A = 26 \qquad [13]$$

$$\delta^+_{crit} = 0.865\ Re^{1/2}{}_{crit} \qquad [14]$$

The film-flow thickness is divided into small increments which are very small adjacent to the wall and then larger beyond the wall and back to small adjacent to the free surface. The number of nodes in x-direction is m nodes; while the number of nodes in y-direction is n nodes. The procedure is to formulate differential equations into finite difference form relating the value of each of the variables at a point in the flow to that at surrounding points by algebraic relationships. A numerical solution is then obtained for a specified mode throughout the flow field by a Gauss-Seidel point iterative method.

The results of such computations give values of all principal variations at each mode in the flow field. From this information, velocity distribution, temperature distribution, local heat transfer coefficients, or any other parameter may be calculated.

A number of nodes in y-direction as n=31, and in x-direction as m=31 and a mish size of 31x31 can be used. The arbitrary momentum and energy balance differential equations of fluid flow in x and y directions can be re-written as follows:

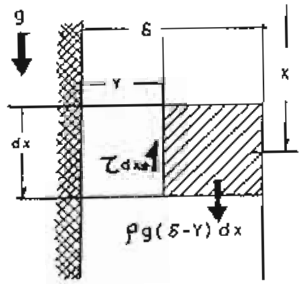


FIGURE (1) FORCE BALANCE ON A FLUID ELEMENT IN A FREELY-FALLING FILM

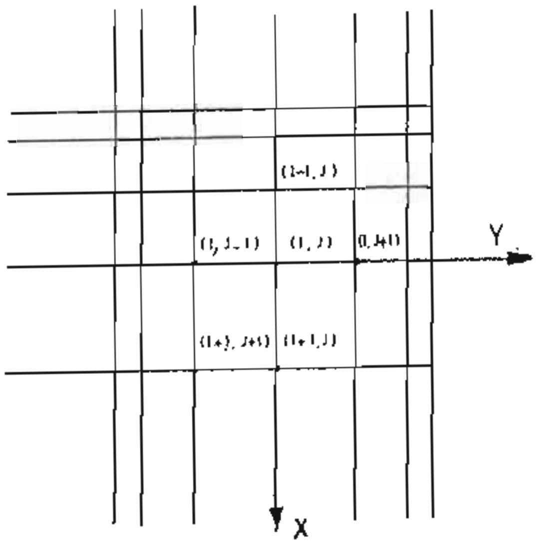


FIGURE (2)- A COMPUTER DOMAIN

$$1-\frac{y^+(J)}{\delta^+(I)}=\left(1+\frac{\varepsilon_M(I,J)}{\gamma}\right)\left\{\frac{[U^+(I,J+1)-U^+(I,J)]\left(\frac{y^+(J)-y^+(J-1)}{y^+(J+1)-y^+(J)}\right)+[U^+(I,J)-U^+(I,J-1)]\left(\frac{y^+(J+1)-y^+(J)}{y^+(J)-y^+(J-1)}\right)}{(y^+(J+1)-y^+(J-1))}\right\} \quad [15]$$

$$\frac{q(I,J)}{q_w(I,1)}=\frac{1}{Pr}\left[1+\frac{Pr}{Pr_t(I,J)}\cdot\frac{\varepsilon_M(I,J)}{\gamma}\right]\left\{\frac{[T^+(I,J+1)-T^+(I,J)]\left(\frac{y^+(J)-y^+(J-1)}{y^+(J+1)-y^+(J)}\right)+[T^+(I,J)-T^+(I,J-1)]\left(\frac{y+(J+1)-y^+(J)}{y^+(J)-y^+(J-1)}\right)}{(y^+(J+1)-y^+(J-1))}\right\} \quad [16]$$

$$U^* = \sqrt{\frac{{}_w(I,1)}{\gamma}} = \sqrt{g\delta(I)} \quad [17]$$

$$y^+(J) = \frac{U^*\, y(J)}{\gamma} \quad [18]$$

$$u^+(I,J) = \frac{u(I,J)}{u^*} \quad [19]$$

$$\delta^+(I) = \frac{U^*(I).\ \delta(I)}{\gamma} \quad [20]$$

$$T^+(I,J) = \frac{\varphi C\rho U^*(I)(T_o(1,1)-T(I,J))}{q_w(I,1)} \quad [21]$$

$$q_w(I,1) = -\left(k+\rho C_p\frac{\varepsilon_H}{\gamma}\right)\frac{T(I,2)-T(I,1)}{y(2)} \quad [22]$$

$$\frac{\varepsilon_H(I,J)}{\gamma} = -\frac{1}{2} + \frac{1}{2}\sqrt{1+4k^2\, y^+(J)^2\left(1-\frac{y^+(J)^2}{\delta^+(I)}\right)}$$

$$\left\{1-\exp\left[-\frac{y^+(J)}{26}\left(1-\frac{y^+(J)}{\delta^+(I)}\right)\right]\right\}^{1/2}\left(1-\frac{0.865\, Re_{crit}}{\delta^+(I)}\right) \quad [23]$$

$$Pr_t\,(I,J) = 1.4\, Exp\left(-15\,\frac{y^+(J)}{\delta^+(I)}\right) + 0.66 \quad [24]$$

The boundary conditions for both in heating and evaporation processes are the follows:

	Evaporation	Heating	
$X^+ = 0$	$T^+ = 0$	$T^+ = T_o^+$	[25]
$Y^+ = 0$	$\frac{1}{Pr}\frac{\partial T^+}{\partial y^+} = 1$	$\frac{1}{Pr}\frac{\partial T^+}{\partial y^+} = 1$	[26]
$Y^+ = \delta^+$	$T^+ = 0$	$\frac{\partial T^+}{\partial y^+}$	[27]

The initial conditions for both in heating and evaporation processes are given in Table (1).

Table (1): The initial condition of using fluid properties

Process	Fluid	Initial Temp. T_o=°C	Press. (p)atm	Prandtl Number (Pr)	Kapitza (Ka)	Reynolds Number Re_{crit}
Heating	Water	20	1	6.96	2.55×10^{-11}	1112
	Water	100	1	1.75	2.82×10^{-12}	1386
Evaporation	Water	99.6	1	1.78	3.15×10^{-13}	1690

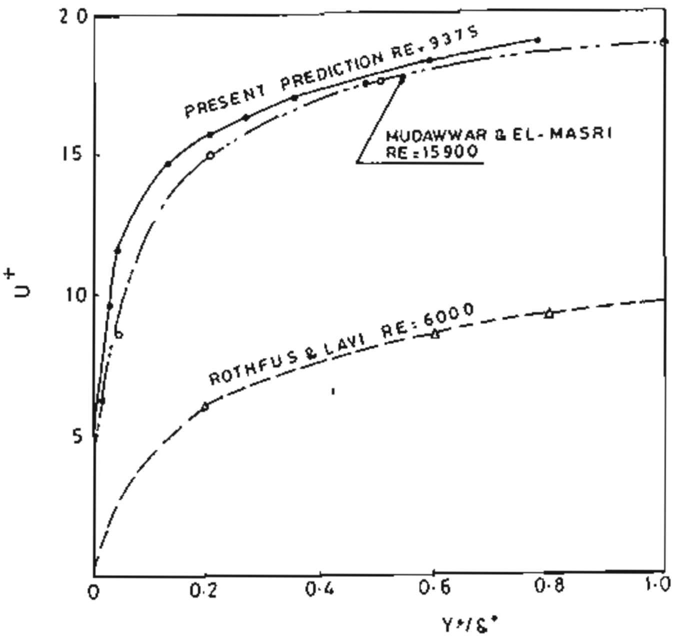


FIGURE (3)- VELOCITY DISTRIBUTION IN FAILING FILM

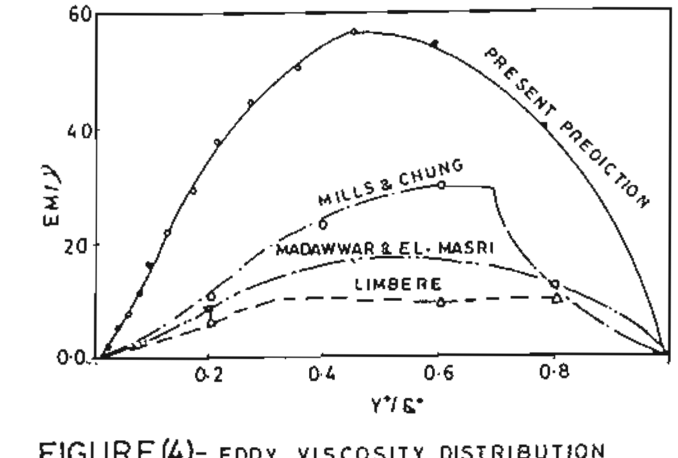


FIGURE (4)- EDDY_VISCOSITY DISTRIBUTION ACROSS A VERTICAL EVAPORATING WATER FILM AT 100°C AND RE=9375

By using the finite difference technique equations [15] to [27] are formulated altogether into a Fortran language computer programme using finite difference technique with iterative method and run on a Personal Computer.

The flow is assumed two dimensional, X-direction increasing toward the flow down stream, while y-direction is normal to the wall surface and starting from the wall surface towards the free surface. The film Reynolds number is given by:

$$Re = 4 \frac{\Gamma}{\mu} = 4 \sum_{J=2}^{J=n} \frac{u^{+}(I,J)(y(J)-y(J-1))}{n \times \mu} \qquad [28]$$

where Γ is the mass flow rate per unit film perimeter.

RESULTS AND DISCUSSION:

The arbitrary equations of fluid and heat flow of the falling film as shown in Fig. 1, are formulated into finite difference form. The flow is considered turbulent, two-dimensional, steady, and constant properties. The thin film of flow has been divided into nodes in both x and y directions. Small increments have been considered adjacent to the wall and adjacent to the freely surface as seen in Fig. 2, because the temperature, velocity and eddy viscosity are changes exceedingly in these regions. The procedure of solution is to solve the arbitrary momentum and energy differential equations, formulated into finite difference form utilizing the accurate boundary conditions around the control film which has been considered. Gas-Seidal point iterative method is applied to obtain an accurate solution. Eddy viscosity, temperature, and the velocity distribution within the flow field are obtained and plotted in Figures 3, 4, 5 and 6. Also Reynolds number and heat transfer coefficient are calculated, and plotted in Figures 7 and 8.

Eddy viscosity is calculated by solving Equation [23], and the present predictions are compared with the other values obtained by Mills & Chung (1973), Mudawwar & El-Masri (1986), and Limberg (1973).

Shapely, the present results are in good agreement with others. But in values, the present values are higher than the others. Finite differences technique is applied for calculating the present values of eddy viscosity utilizing the accurate boundary conditions, while the previous values are calculated by normal integration methods.

Figure 3 shows the dimensionless velocity distribution within the vertical falling film thickness. Present predicted values are plotted along with the values of Rothfus & Lavi (1977), and Mudawwar & El-Masri (1986) at different values of Reynolds numbers (9375, 6000 and 15900 respectively). The present values are in good agreement with Mudawwar & El-Masri (1986). These are twice as compared to the values obtained by Rothfus & Lavi, due to utilizing different forms of calculating the eddy viscosity.

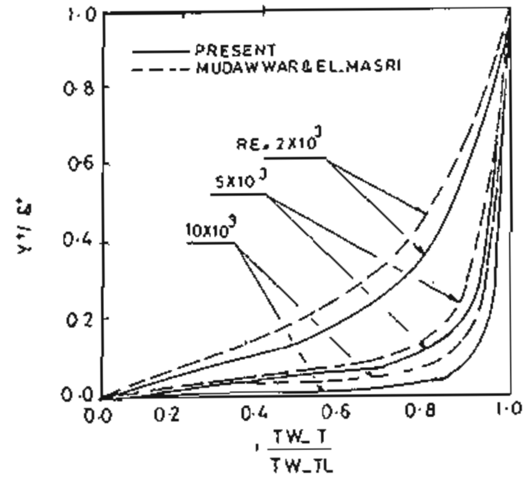


FIGURE (5)-TEMPERATURE DISTRIBUTION ACROSS HEATED WATER FILMS AT 20°C

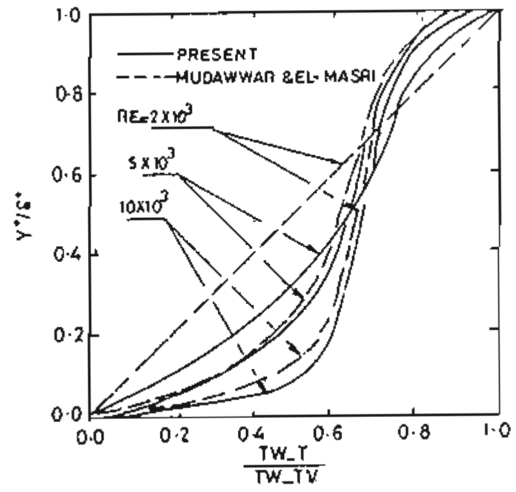


FIGURE (6)-TEMPERATURE DISTRIBUTION ACROSS EVAPERATING WATER FILMS AT 100°C.

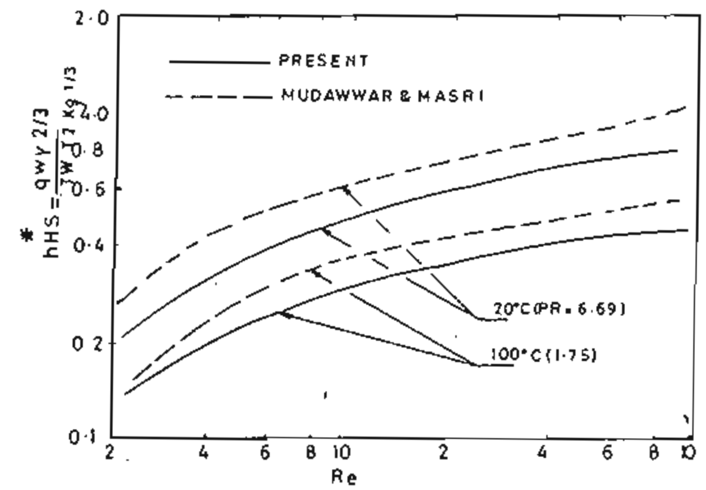
Temperature distribution across heated and evaporated falling water films are plotted in Figures 5, and 6 respectively. The comparison between present and previous values obtained by Mudawwar & El-Masri (1986) are shown in both the Figures, at different values of Reynolds numbers. A good agreement is clearly observed for all cases.

Dimensionless heat transfer coefficients are plotted in Figures 7 and 8 for the heated and evaporating water falling films, respectively. In both the Figures the present predictions are compared with the values obtained by Mudawwar & El-Masri (1986) and a good agreement is obtained for both heating and evaporating cases.

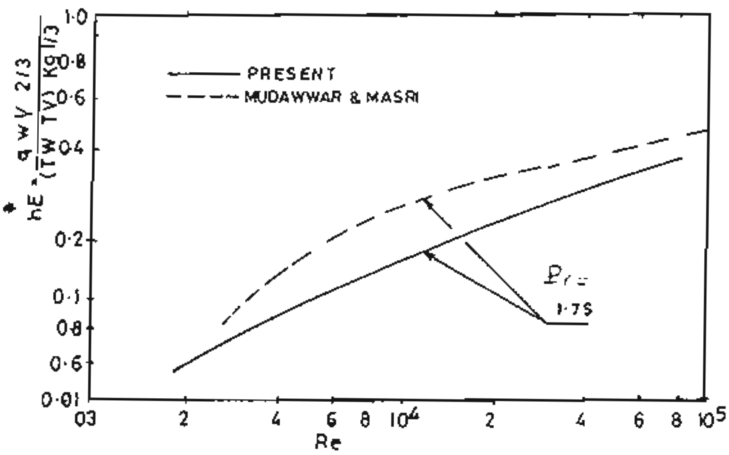
By employing the eddy viscosity model of Mudawwar & El-Masri (1986), the present results of heat transfer coefficients are approximately 10 percent less in both heating and evaporating cases than those of Mudawwar & El-Masri (1986), as these authors used accurate boundary conditions.

CONCLUSIONS:

Finite difference technique is applied successfully for solving the falling water films in both heating and evaporating cases. The present results are compared with previous results obtained by other investigators and are found in good agreement. Also the new technique of the eddy diffusivity model of Mudawwar & El-Masri (1986) is employed. The finite difference technique is easy to apply and only the difficulty is how to choose the accurate boundary conditions made possible by measuring or guessing. Also the new technique can be easily applied for another problems for falling films such as other liquids or for horizontal tubes.



FIGURE(7) - HEAT TRANSFER COEFFICIENT FOR HEATED FILMS BASED ON THE SURFACE TEMPERATURE



FIGURE(8)-HEAT TRANSFER COEFFICIENT FOR EVAPORATING, WATER FILMS.

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