Lawrence Livermore Laboratory

Capillary Liquid Evaporation from Wick Covered Plates--Theory

J. H. Van Sant

June 2, 1969

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ABSTRACT

Differential equations and associated parameters are derived for heat transfer to a thin liquid-saturated wick, as in the evaporator section of a "heat pipe." Prescribed are a numerical method of solution and a procedure for experimental measurements of heat transfer in the flat plate model. This effort is a part of the Project CLEER program which is currently sponsored by the Mechanical Engineering Department research account.

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NOMENCLATURE

 c = Specific heat e = Enthalpy g = Gravitational acceleration g_c = Gravitational constant h = Heat transfer coefficient k = Thermal conductivity K = Inverse permeability $\dot{m}$ = Mass flux p = Pressure q_p = Plate heat flux r = Curvature of liquid in capillary t = Temperature t_0 = Reservoir temperature u = Velocity parallel to plate v = Velocity normal to plate x = Distance from leading edge of plate and parallel to surface x_0 = Unheated portion of wick y = Normal distance from plate surface z_0 = Elevation of plate leading edge from reservoir

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Nomenclature (cont'd) α = Thermal diffusivity β = Contact angle of liquid δ = Wick thickness ϵ = Wick porosity μ = Dynamic viscosity of liquid ν = Kinematic viscosity of liquid ρ = Liquid density σ = Surface tension θ = Angle of plate inclination τ = Time

Dimensionless parameters

$$\mathcal{E} = c(t_p - t_v)/e_{v-l}$$

$$\mathcal{G} = \epsilon^2 \delta^3 g_c / g_c \nu^2$$

$$\mathcal{K} = \delta^2 \epsilon^2 K$$

$$Nu = h\delta/k$$

$$P = (p_v - p)g_c / \rho g \delta$$

$$Pr = \nu/\alpha$$

$$Q = q_p \delta c / k e_{l-v}$$

 S = Dimensionless stream function

$$T = (t - t_v)/(t_p - t_v) \text{ or } (t - t_v)k/q_p \delta$$

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Nomenclature (cont'd)

$$U = \epsilon u \delta / \nu$$

$$V = \epsilon v \delta / \nu$$

$$W = \text{Dimensionless vorticity}$$

$$X = x / \delta$$

$$X_0 = x_0 / \delta$$

$$Y = y / \delta$$

$$Z = z_0 / \delta$$

$$Z^* = 2\sigma g_c / r_e \delta \rho g$$

$$T = \tau \nu / \delta^2$$

Subscripts

d = "Dry-up"

l = Liquid

v = Vapor

p = Plate

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INTRODUCTION

The heat transfer device commonly known as a "heat-pipe" [1]* is constructed basically of a vapor chamber lined with some kind of capillary material called a wick, as illustrated in Fig. 1. A capillary liquid fills the wick and pure vapor from the liquid fills the remainder of the chamber. When heat is supplied to one end of the chamber, the liquid evaporates. By cooling the other end, the vapor condenses and then returns to the heated end by capillary flow in the wick.

The region to which attention is directed henceforth is the evaporator section where a rather unusual heat transfer phenomena occurs. The chamber surface is cooled by convection and conduction in a porous media where non-uniform liquid velocities exist and the liquid evaporates at the free surface. This complex combination of conditions does not allow one to easily predict heat transfer characteristics and operating limits of the evaporator. Consequently, a model of the evaporator is prescribed so that heat-transfer and fluid-flow in the wick can be analyzed. A solution of the model would provide valuable information for heat-pipe designs as well as many other possible applications of surface cooling by saturated wicks.

*Numbers in brackets refer to list of references.

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Fig. 1 An Illustration of the Heat-Pipe Concept

A flat plate geometry of the wick-liquid evaporation model is chosen since it is easier to study than the cylindrical geometry existing in most heat-pipes. Also, the flat plate is a close approximation to the condition in heat-pipes since wicks are usually thin compared to their radius. The mechanics of mass, momentum and energy transport in the wick are analyzed to derive differential equations describing local conditions of fluid pressure, temperature and velocity. These equations and appropriate boundary conditions are then non-dimensionalized to determine parameters that describe properties, geometry and boundary conditions. Numerical and experimental procedures are then prescribed for determining local heat transfer rates from the plate to the wick and conditions for wick "dry-up."

An experimental apparatus of the flat plate model has already been constructed as part of the project CLEER program. This analysis provides information for determining the procedure of testing.

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THE MODEL

A semi-infinite plate inclined at some angle θ is covered with a layer of wicking material of constant thickness δ . The wick is kept saturated with a capillary liquid by one end of it being in a reservoir as seen in Fig. 2. Liquid evaporates from the wick due to heat supplied from the plate at either constant temperature t_p or constant flux q_p . The initial height z_0 and length x_0 correspond to the elevation change and length of the adiabatic section between the condenser and evaporator in the heat-pipe.

Fig. 2 Model of wick covered plate

Either local heat transfer rates or temperatures of the plate and location of wick "dry-up" are needed.

A number of assumptions about heat transfer and wick conditions are made before developing the differential equations. They include:

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1. The wick has isotropic properties in all directions.
2. The wick is completely saturated up to either the point of "dry-up" or the end of the wick.
3. The wick temperature in the unheated section x_0 shall be equal to the reservoir temperature t_0 .
4. The vapor surface of the wick shall have a temperature equal to the vapor temperature of the liquid and be constant over the heated length.
5. Liquid properties are constant.
6. The plate is inclined in only the x-direction.
7. Liquid velocity in the wick at $x=0$ is uniform.
8. Steady-state conditions exist.
9. Conditions are constant in the direction normal to the x-y plane.
10. There is no interaction between the vapor flow and the wick flow.
11. At the position of "dry-up," the liquid is bounded by a plane normal to the plate surface.
12. Flow is incompressible.
13. There is no vapor in the wick except beyond the location of "dry-up."

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DIFFERENTIAL EQUATIONS

Continuity

Consider a rectangular element of the wick dimensioned Δx by Δy . If the void fraction or porosity of the wick is ϵ and u and v are the superficial pore velocities* in the x and y directions, the conservation of mass flow requires that

$$([\rho\epsilon u]_x - [\rho\epsilon u]_{x+\Delta x})\Delta y + ([\rho\epsilon v]_y - [\rho\epsilon v]_{y+\Delta y})\Delta x = 0 \quad (1)$$

Dividing this expression by $\rho\epsilon\Delta x\Delta y$ and letting $\Delta x \rightarrow 0$, $\Delta y \rightarrow 0$ yields

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

*Actual velocities in the wick are probably undeterminable because flow areas of discrete flow channels are not constant and non-uniform velocity profiles exist in each channel. Consequently, effective directional velocities are defined as $u = \dot{m}_x / \rho\epsilon$, $v = \dot{m}_y / \rho\epsilon$, where $\dot{m}_x$ and $\dot{m}_y$ are the mass fluxes in the x - and y -directions.

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Momentum

If a rectangular element of wick is again considered, the conservation of momentum principle requires that

$$\Delta M = F_p + F_d + F_b \quad (3)$$

where ΔM is the net change in momentum and F_p , F_d and F_b are pressure, drag and body forces acting on the elements of fluid. Since there are forces in both x- and y-directions, equation (3) must be applied to each one individually.

x-direction:

$$\Delta M_x = ([\dot{m}_x u]_{x+\Delta x} - [\dot{m}_x u]_x) \Delta y + ([\dot{m}_y u]_{y+\Delta y} - [\dot{m}_y u]_y) \Delta x \quad (4)$$

$$F_{p_x} = ([\epsilon p]_x - [\epsilon p]_{x+\Delta x}) \Delta y \quad (5)$$

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$$F_{d_x} = -K\mu\epsilon^2 u \Delta x \Delta y^* \quad (6)$$

$$F_{b_x} = -\frac{\rho g}{g_c} \epsilon \sin \theta \Delta x \Delta y \quad (7)$$

Using (4), (5), (6) and (7) in (3) yields

$$([\dot{m}_x u]_{x+\Delta x} - [\dot{m}_x u]_x) \Delta y - ([\dot{m}_y u]_{y+\Delta y} - [\dot{m}_y u]_y) \Delta x =$$

$$([P]_x - [P]_{x+\Delta x}) \epsilon \Delta y - K\mu\epsilon^2 u \Delta x \Delta y \quad (8)$$

Dividing (8) by $\Delta x \Delta y$ and letting $x \rightarrow 0$, $y \rightarrow 0$ gives

$$\frac{\partial(\dot{m}_x u)}{\partial x} + \frac{\partial(\dot{m}_y u)}{\partial y} = -\epsilon \frac{\partial p}{\partial x} - K\mu\epsilon^2 u - \frac{\rho g \epsilon \sin \theta}{g_c} \quad (9)$$

Since $\dot{m}_x = \rho \epsilon u$, $\dot{m}_y = \rho \epsilon v$ and $\frac{\partial \dot{m}_x}{\partial x} + \frac{\partial \dot{m}_y}{\partial y} = 0$ from (2), (9) becomes

$$\boxed{\rho \epsilon \left(u \frac{\partial u}{\partial x} + v \frac{\partial v}{\partial y} \right) + \epsilon \frac{\partial p}{\partial x} + K\mu\epsilon^2 u + \frac{\rho g \epsilon \sin \theta}{g_c}} \quad (10)$$

* Darcy's law for flow through a porous media is given as $\Delta p_x = -K\mu \dot{m}_x \Delta x / \rho$ [2]

in which K is a constant of proportionality or the reciprocal of permeability.

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y-direction:

$$\Delta M_y = ([\dot{m}_y v]_{y+\Delta y} - [\dot{m}_y v]_y) \Delta x + ([\dot{m}_x v]_{x+\Delta x} - [\dot{m}_x v]_x) \Delta y \quad (11)$$

$$F_p = ([\epsilon P]_y - [\epsilon P]_{y+\Delta y}) \Delta x \quad (12)$$

$$F_{dy} = -K \mu \epsilon^2 v \Delta x \Delta y \quad (13)$$

$$F_{by} = -\frac{\rho g}{g_c} \epsilon \cos \theta \Delta x \Delta y \quad (14)$$

Using (11), (12), (13) and (14) in (3) and using the same treatment as in (9) yields

$$\boxed{\rho \epsilon \left(u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} \right) + \epsilon \frac{\partial P}{\partial y} + K \mu \epsilon^2 v + \frac{\rho g}{g_c} \epsilon \cos \theta} \quad (15)$$

Energy

The conservation of energy principle requires that the net energy passing through the boundaries of the rectangular element must be zero. Since there is mass transport, both conduction and convection must be considered.

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Thus

$$E_{cv} + E_{cd} = 0^* \quad (15)$$

The net convection is given as

$$E_{cv} = ([\rho ect]_{x+\Delta x} - [\rho ect]_x) \Delta y + ([\rho ect]_{y+\Delta y} - [\rho ect]_y) \Delta x \quad (17)$$

The conduction transfer is determined from Fourier's law as

$$E_{cd} = ([-k \partial t / \partial x]_{x+\Delta x} - [-k \partial t / \partial x]_x) \Delta y + ([-k \partial t / \partial y]_{y+\Delta y} - [-k \partial t / \partial y]_y) \Delta x \quad (18)$$

Note that the thermal conductivity k must include the effects of both the wick material and the liquid.

* Kinetic energy and viscous dissipation are presumed negligible.

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Substituting (17) and (18) into (16) then dividing by $\rho c \Delta x \Delta y$ and
letting $x \rightarrow 0$, $y \rightarrow 0$ results in

$$\epsilon \left(\frac{\partial u t}{\partial x} + \frac{\partial v t}{\partial y} \right) = \frac{k}{\rho c} \left(\frac{\partial}{\partial x} \cdot \frac{\partial t}{\partial x} + \frac{\partial}{\partial y} \cdot \frac{\partial t}{\partial y} \right) \quad (19)$$

By using the continuity equation (2) and re-arranging terms gives

$$\epsilon u \frac{\partial t}{\partial x} + \epsilon v \frac{\partial t}{\partial y} = \alpha \left(\frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2} \right) \quad (20)$$

where α is the thermal diffusivity.

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BOUNDARY CONDITIONS

The differential equations describe u , v , t and p in the space $0 \leq x \leq x_d$ and $0 \leq y \leq \delta$ where x_d is the location of wick "dry-up" or the end of the wick. The conditions for dependent variables on these boundaries are specified as follows:

Temperature

$$[t]_{x=0} = t_o \quad (21)$$

$$\left[\frac{\partial t}{\partial x} \right]_{x=x_d} = 0 \quad (22)$$

$$[t]_{y=0} = t_p \quad \text{or} \quad \left[-k \frac{\partial t}{\partial y} \right]_{y=0} = q_p^* \quad (23)$$

$$[t]_{y=\delta} = t_v \quad (24)$$

x-Velocity

$$[u]_{x=0} = u_o \quad (25)$$

$$[u]_{x=x_d} = 0 \quad (26)$$

$$\left[\frac{\partial u}{\partial y} \right]_{y=0} = 0 \quad (\text{slip flow}) \quad (27)$$

y-Velocity

$$[v]_{x=0} = 0 \quad (28)$$

$$\left[\frac{\partial v}{\partial x} \right]_{x=x_d} = 0 \quad (\text{slip flow}) \quad (29)$$

*The temperature condition at $y=0$ depends on whether the plate temperature t_p or plane heat flux q_p are specified.

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$$[V]_{y=0} = 0 \quad (30)$$

$$[V]_{y=\delta} = \frac{-k \partial t / \partial y}{\epsilon \rho e_{v-l}} \quad (31)$$

The last condition is determined by assuming heat energy leaving the wick vapor surface is supplied by conductive and convective transports in the liquid to the vapor surface, i.e.,

$$\rho_v v_v e_v = \left[\epsilon \rho v e_l - k \frac{\partial t}{\partial y} \right]_{y=\delta} \quad (32)$$

where e_l and e_v are liquid and vapor enthalpies. Since $\rho_v v_v = \rho e_v$ by reason of continuity, then (31) results from (32) where $e_{v-e} = e_v - e_l$.

Pressure

The pressure loss in the unheated portion of the wick will be due to frictional and gravitational losses. Thus, assuming the pressure at the reservoir is the vapor pressure,

$$[P]_{x=0} = p_v - K \mu \epsilon^2 u x_0 - \frac{\rho g z_0}{g_c} \quad (33)$$

At the end of the wick on the vapor surface, the pressure difference between the liquid and vapor is caused by the capillary forces in the wick pores. Assuming this phenomenon acts much like that in a capillary tube,

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the pressure difference can be stated as [3]

$$P_v - P_l = \frac{2\sigma \cos \beta}{r} \quad (34)$$

where σ is the liquid surface tension, β is the contact angle and r is the radius of curvature of the liquid-vapor interface. If the wick is saturated over its entire length, the

radius r will probably adjust to provide the pressure necessary to support flow for the required evaporation rate. If, however, there is a "dry-up" condition, the radius r becomes a minimum at x_d . This minimum will most likely be equal to some effective pore radius. During this condition, β will be very small and (34) can be stated as

$$[P]_{x=x_d} = P_v - 2\sigma/r_e \quad (35)$$

where r_e is the effective pore radius. A method suggested [4] for measuring r_e is to observe the vertical height the liquid will rise in a sample of wick during static conditions. This height z^* can then be used in (34) to estimate r_e by

$$r_e = \frac{2\sigma}{\rho z^* g / g_c} \quad (36)$$

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The effective pore radius r_e for capillary forces might not be the same during dynamic conditions of evaporation as during static conditions. If this is the case, then a dynamic experiment of some sort must be devised to measure r_e .

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DIMENSIONLESS EQUATIONS AND PARAMETERS

The dimensionless form of velocity normally used in convective heat transfer analyses is the Reynolds number. Therefore, let

$$U = \frac{u\delta}{v}, \quad V = \frac{v\delta}{v}, \quad P = \frac{p_v - p}{\rho\delta g/g_c} \quad (37)$$

$$X = \frac{x}{\delta}, \quad Y = \frac{y}{\delta}$$

If the plate temperature is specified as t_p , let

$$T = \frac{t - t_v}{t_p - t_v} \quad (38)$$

If the plate heat flux is given as q_p , let

$$T = \frac{(t - t_v)k}{q_p\delta} \quad (39)$$

When, u , v , t , p , x and y in the continuity, momentum and energy equations (2), (10), (15) and (20) are replaced by quantities given above, the following dimensionless equations result.

Continuity

$$\boxed{\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0} \quad (40)$$

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Momentum

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} - G \frac{\partial P}{\partial x} + \kappa u + G \sin \theta = 0 \quad (41)$$

$$u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} - G \frac{\partial P}{\partial y} + \kappa v + G \cos \theta = 0 \quad (42)$$

where

$$G = \frac{\epsilon^2 \delta^3 g}{v^2 g_c}, \quad \kappa = \epsilon \delta^2 K$$

Energy

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \frac{1}{Pr} \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \quad (43)$$

where Pr = Prandtl number = ν/α Boundary Conditions

Conditions stated in (21) through (31) can be restated in the following manner:

$$[T]_{x=0} = T_o \quad (44)$$

$$\left[\frac{\partial T}{\partial x} \right]_{x=x_d} = 0 \quad (45)$$

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$$[T]_{Y=0} = T_p \quad \text{or} \quad \left[-\frac{\partial T}{\partial Y}\right]_{Y=0} = 1 \quad (46)$$

$$[u]_{X=0} = u_o \quad (47)$$

$$[u]_{X=X_d} = 0 \quad (48)$$

$$\left[\frac{\partial u}{\partial Y}\right]_{Y=0} = 0 \quad (49)$$

$$[V]_{X=0} = 0 \quad (50)$$

$$\left[\frac{\partial V}{\partial X}\right]_{X=X_d} = 0 \quad (51)$$

$$[V]_{Y=0} = 0 \quad (52)$$

$$[V]_{Y=1} = \left[-\frac{\varepsilon}{Pr} \frac{\partial T}{\partial Y}\right]_{Y=1} \quad \text{or} \quad [V]_{Y=1} = \left[-\frac{Q}{Pr} \frac{\partial T}{\partial Y}\right]_{Y=1} \quad (53)$$

where $\varepsilon = c(t_p - t_v)/e_{v-l}$,

$$[P]_{X=0} = KX_o u_o / \alpha + Z_o \quad (54)$$

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where $X_o = x_o/\delta$, $Z_o = z_o/\delta$

$$[P]_{X=X_d} = Z^* \text{ when "dry-up" occurs} \quad (55)$$

where $Z^* = \frac{2\sigma}{r_e \delta \rho g / g_c}$

Heat Transfer

Local heat transfer rates from the plate should be expressed in terms of a convenient parameter. Consequently, the commonly used heat transfer coefficient shall be defined as

$$h = \frac{q_p}{(t_p - t_v)} \quad (56)$$

If the plate temperature is specified rather than heat flux, then q_p must be replaced by $\left[-k \frac{\partial t}{\partial y} \right]_{y=0}$

Rewriting (56) in terms of the selected dimensionless parameters yields

$$Nu = - \left[\frac{\partial T}{\partial Y} \right]_{Y=0} \quad (57)$$

for a constant temperature plate and

$$Nu = [T^{-1}]_{Y=0} \quad (58)$$

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for a constant heat flux plate, where Nu =Nusselt number= $h\delta/k$.

Reviewing the foregoing dimensionless equations, boundary conditions and parameters, we can see that Nu will be dependent on the property and geometry parameters K , G , Pr , T_0 , X_0 , X , Z_0 , Z^* , θ and either $\mathcal{E}$ or Q . The independent variable X is the only space parameter, thus Nu should be determined at discrete values of X with the other parameters treated as constants.

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METHOD OF SOLUTION

If transient conditions had been included in the development of the dimensionless equations (40-43), the result would be

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (41)$$

$$\frac{\partial u}{\partial \tau} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} - G \frac{\partial P}{\partial x} + \kappa u + G \sin \theta = 0 \quad (59)$$

$$\frac{\partial v}{\partial \tau} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} - G \frac{\partial P}{\partial y} + \kappa v + G \cos \theta = 0 \quad (60)$$

$$\frac{\partial T}{\partial \tau} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \frac{1}{Pr} \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \quad (61)$$

where T is a dimensionless time parameter.

The pressure terms can be eliminated by taking $\partial/\partial x$ of (60) and $\partial/\partial y$ of (59) and subtracting. Presuming that derivatives are interchangeable, the result is

$$\frac{\partial W}{\partial \tau} + u \frac{\partial W}{\partial x} + v \frac{\partial W}{\partial y} + \kappa W = 0 \quad (62)$$

where $W = \text{dimensionless vorticity function} = \partial v / \partial x - \partial u / \partial y$.

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The velocities can be related to a dimensionless stream function as

$$U = \partial S / \partial Y, \quad V = -\partial S / \partial X \quad (63)$$

which allows the vorticity function to be stated as

$$W = -(\partial^2 S / \partial X^2 + \partial^2 S / \partial Y^2) \quad (64)$$

Equations (61), (62) and (64) can now be used to solve for S, T and W and then (63) can be used to determine U and V. The boundary conditions given in (47) through (53) must be revised for describing S and W.

$$[\partial S / \partial Y]_{X=0} = U_0 \quad (65)$$

$$[S]_{X=X_d} = 0 \quad (66)$$

$$[S]_{Y=0} = 0 \quad (67)$$

$$[\partial S / \partial X]_{Y=1} = \frac{E}{Pr} \frac{\partial T}{\partial Y} \quad \text{or} \quad \frac{Q}{Pr} \frac{\partial T}{\partial Y} \quad (68)$$

$$[W]_{X=0} = -\partial^2 S / \partial X^2 \quad (69)$$

$$[W]_{X=X_d} = 0 \quad (70)$$

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$$[W]_{Y=0} = 0 \quad (71)$$

$$[W]_{Y=1} = -\left(\frac{\partial^2 S}{\partial X^2} + \frac{\partial^2 S}{\partial Y^2}\right) \quad (72)$$

A numerical method of solution is prescribed for solving (61), (62) and (64) which is described as an explicit forward time differencing scheme [5]. The differential equations are to be expressed in finite difference form using an i, j notation for a rectangular array of node points in the region $0 \leq X \leq X_d$, $0 \leq Y \leq 1$ with $1 \leq i \leq n$, $1 \leq j \leq m$. A requirement for calculating stability in this scheme is that derivatives having variable coefficients must use backward differences when the coefficient is positive and forward differences when the coefficient is negative. Also, there is a limit on the time step size which will be given.

The energy equation
(51) in difference form
with U and V positive
is

$$\frac{T_{i,j}^{n+1} - T_{i,j}^n}{\Delta T} + U_{i,j} \frac{(T_{i,j} - T_{i-1,j})}{\Delta X} + V_{i,j} \frac{(T_{i,j} - T_{i,j-1})}{\Delta Y} =$$

$$\frac{1}{Pr} \left(\frac{T_{i,j} + T_{i+1,j} - 2T_{i,j}}{\Delta X^2} + \frac{T_{i,j-1} + T_{i,j+1} - 2T_{i,j}}{\Delta Y^2} \right) \quad (73)$$

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where terms without a superscript signify values of time level n . Solving for $T_{i,j}^{n+1}$ yields

$$\begin{aligned} T_{i,j}^{n+1} = & \left[(1/\Delta\tau - u_{i,j}/\Delta x - v_{i,j}/\Delta y - 2/P_r \Delta x^2 - 2/P_r \Delta y^2) T_{i,j} + \right. \\ & (u_{i,j}/\Delta x + 1/P_r \Delta x^2) T_{i-1,j} + (1/P_r \Delta x^2) T_{i+1,j} + \\ & \left. (v_{i,j}/\Delta y + 1/P_r \Delta y^2) T_{i,j-1} + (1/P_r \Delta y^2) T_{i,j+1} \right] \Delta\tau \end{aligned} \quad (74)$$

The vorticity equation (62) in difference form with U and V positive is written

$$\frac{W_{i,j}^{n+1} - W_{i,j}}{\Delta\tau} + \frac{u_{i,j}(W_{i,j} - W_{i-1,j})}{\Delta x} + \frac{v_{i,j}(W_{i,j} - W_{i,j-1})}{\Delta y} + \kappa W_{i,j} = 0 \quad (75)$$

and

$$\begin{aligned} W_{i,j}^{n+1} = & \left[(1/\Delta\tau - u_{i,j}/\Delta x - v_{i,j}/\Delta y - \kappa) W_{i,j} + \right. \\ & \left. (u_{i,j}/\Delta x) W_{i-1,j} + (v_{i,j}/\Delta y) W_{i,j-1} \right] \Delta\tau \end{aligned} \quad (76)$$

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The stream function equation (64) in difference form becomes

$$-W_{i,j} = \frac{S_{i+1,j} + S_{i-1,j} - 2S_{i,j}}{\Delta X^2} + \frac{S_{i,j-1} + S_{i,j+1} - 2S_{i,j}}{\Delta Y^2} \quad (77)$$

Solving for $S_{i,j}$ yields

$$S_{i,j} = \left[\frac{(S_{i+1,j} + S_{i-1,j})}{\Delta X^2} + \frac{(S_{i,j-1} + S_{i,j+1})}{\Delta Y^2} + W_{i,j} \right] \left(\frac{2}{\Delta X^2} + \frac{2}{\Delta Y^2} \right) \quad (78)$$

Values of T and W at new time levels can be determined from values at present time levels using (74) and (76). Values of S at each time level can be computed using the Gause-Sidel method of successive displacements [6].

The requirement for time step size is that the coefficients of $T_{i,j}$ or $W_{i,j}$ in (74) or (76) must be positive. The coefficient in (76) will give the smallest limit on $\Delta \tau$. Thus,

$$U_{i,j}/\Delta X + V_{i,j}/\Delta Y - K \leq 1/\Delta \tau \quad (79)$$

Some of the boundary conditions are stated as derivatives which must be given in difference form. Condition (45) used in (73) gives

$$\begin{aligned} T_{i,j}^{n+1} = & \left[\left(1/\Delta \tau - V_{i,j}/\Delta Y - 2/Pr \Delta X^2 - 2/Pr \Delta Y^2 \right) T_{i,j} + \right. \\ & \left(2/Pr \Delta X^2 \right) T_{i-1,j} + \left(V_{i,j}/\Delta Y + 1/Pr \Delta Y^2 \right) T_{i,j-1} + \\ & \left. \left(1/Pr \Delta Y^2 \right) T_{i,j+1} \right] \Delta \tau \end{aligned} \quad (80)$$

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Condition (46) given in terms of a three point difference is

$$\frac{3T_{i,1} - 4T_{i,2} + T_{i,3}}{2\Delta Y} = 1$$

$$\text{or } T_{i,1} = \frac{2\Delta Y - T_{i,3} + 4T_{i,2}}{3} \quad (81)$$

Since $[S]_{X=X_d}=0$, condition (68) can be used to calculate $[S]_{Y=1}$ by numerically integrating from $X_d > X \geq 0$.

$$S_{i,m} = -\frac{\epsilon \Delta X}{Pr} \left[\frac{1}{2} \left[\frac{\partial T}{\partial Y} \right]_{X=X_i, Y=1} + \frac{1}{2} \left[\frac{\partial T}{\partial Y} \right]_{X=X_m, Y=1} + \sum_{k=1}^{n-i-1} \left[\frac{\partial T}{\partial Y} \right]_{X=X_{n-k}, Y=1} \right] \quad (82)$$

where $\left[\frac{\partial T}{\partial Y} \right]_{Y=1} = \frac{3T_{i,m} - 4T_{i,m-1} + T_{i,m-2}}{2\Delta Y}$ is prescribed.

$[S]_{X=0, Y=1}$ is determined from (82) and $[S]_{X=0, Y=0}=0$. Since $[\partial S / \partial Y]_{X=0}$ is a

constant given by (65), values of S on the boundary $X=0$ can be determined by a linear interpolation between $S_{1,1}$ and $S_{1,m}$.

$$S_{1,j} = (S_{1,m})^j / j - 1 \quad (83)$$

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The vorticity boundary condition at $X=0$ given by (69) is estimated by a two point Taylor series expansion as follows:

$$S_{2,j} = S_{1,j} + \Delta X \left[\frac{\partial S}{\partial X} \right]_{X=0} + \frac{\Delta X^2}{2!} \left[\frac{\partial^2 S}{\partial X^2} \right]_{X=0} + \frac{\Delta X^3}{3!} \left[\frac{\partial^3 S}{\partial X^3} \right]_{X=0} + \dots \quad (84)$$

$$S_{3,j} = S_{1,j} + 2\Delta X \left[\frac{\partial S}{\partial X} \right]_{X=0} + \frac{(2\Delta X)^2}{2!} \left[\frac{\partial^2 S}{\partial X^2} \right]_{X=0} + \frac{(2\Delta X)^3}{3!} \left[\frac{\partial^3 S}{\partial X^3} \right]_{X=0} + \dots \quad (85)$$

Multiplying (84) by 8, subtracting (85) from the result and noting that $\left[\frac{\partial S}{\partial X} \right]_{X=0} = 0$ from (50) yields

$$W_{1,j} = - \left[\frac{\partial^2 S}{\partial X^2} \right]_{X=0} = \frac{7S_{1,j} - 8S_{2,j} + S_{3,j}}{2\Delta X^2} \quad (86)$$

The condition (72) for $[W]_{Y=1}$ is determined by central differencing of second derivatives.

$$W_{i,m} = - \left[\frac{S_{i+1,m} + S_{i-1,m} - 2S_{i,m}}{\Delta X^2} + \frac{S_{i,m} + S_{i,m-2} - 2S_{i,m-1}}{\Delta Y^2} \right] \quad (87)$$

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Velocities can, at any interior node, be determined by central differencing of (63).

$$U_{i,j} = \frac{S_{i,j+1} - S_{i,j-1}}{2\Delta Y}, \quad V_{i,j} = \frac{S_{i+1,j} - S_{i-1,j}}{2\Delta X} \quad (88)$$

A three point differencing scheme such as in (81) can be used for computing U and V at the boundaries if a central difference cannot be used, e.g

$$U_{i,m} = \frac{3S_{i,m} - 4S_{i,m-1} + S_{i,m-2}}{2\Delta Y}$$

If the velocity field is established for steady-state conditions, then (41) or (42) can be used to compute pressures at particular locations. For example, if "dry-up" is specified at $X=X_d$, then $P=Z^*$. The pressure at $X=0$ can be determined by numerical integration of (41).

$$P_{1,m} = Z^* - \frac{\Delta X}{Gr} \left[\frac{U_{1,m}}{Z} \left(\left[\frac{\partial U}{\partial X} \right]_{X=0}^{Y=1} - (n-1) G \sin \theta + \sum_{i=1}^{n-1} U_{i,m} \left[\frac{\partial U}{\partial X} \right]_{X=X_i}^{Y=1} + V_{i,m} \left[\frac{\partial U}{\partial Y} \right]_{X=X_i}^{Y=1} + \kappa U_{i,m} \right] \right] \quad (89)$$

where derivatives are replaced by

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$$\left[\frac{\partial u}{\partial x} \right]_{\substack{x=0 \\ y=1}} = \frac{-3u_{1,m} + 4u_{2,m} - u_{3,m}}{2\Delta x} \quad (90)$$

$$\left[\frac{\partial u}{\partial x} \right]_{\substack{x=x_i \\ y=1}} = \frac{u_{i+1,m} - u_{i-1,m}}{2\Delta x} \quad (91)$$

$$\left[\frac{\partial u}{\partial y} \right]_{\substack{x=x_i \\ y=1}} = \frac{3u_{i,m} - 4u_{i,m-1} + u_{i,m-2}}{2\Delta y} \quad (92)$$

The unheated length condition for "dry-up" at $X=X_d$ can thus be estimated from (54).

Local heat transfer from the plate can be estimated from the Nusselt number given in (57).

$$Nu_i = - \left[\frac{\partial T}{\partial y} \right]_{y=0} = \frac{3T_{i,1} - 4T_{i,2} + T_{i,3}}{2\Delta y} \quad (93)$$

A computing procedure using the foregoing difference equations is now prescribed for computing steady-state values of temperature, velocity and heat flux. The algorithmic procedure is as follows:

1. Obtain values of $G, \chi, Pr, T_0, X_d, Z^*, \theta, \Delta T, n, m$ and $\mathcal{E}$ or Q .
2. Assign zero to all values of S, T and W , except $[T]_{x=0} = T_0$ and $[T]_{y=0} = 1$.
3. Use (74), (80) and (81) if applicable to solve for all unknown values of $T_{i,j}^{n+1}$.

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4. Use (76) to solve for $W_{i,j}^{n+1}$ at all interior nodes.
5. Use (78) to solve for all $S_{i,j}$ at all interior nodes.
6. Use (82) and (83) to solve for boundary values of S .
7. Use (86) and (87) to solve for boundary values of W .
8. Use (88) to solve for U and V at all nodes.
9. Test for steady-state conditions, if yes go to step 11.
10. Re-index $T_{i,j} = T_{i,j}^{n+1}$, $W_{i,j} = W_{i,j}^{n+1}$, then go to step 3.
11. Use (39) to solve for $P_{1,m}$ and (54) to determine relationship between X_0 and Z_0 for wick "dry-up" condition.
12. Use (93) to compute Nu_i at $Y=0$.
13. List results.
14. End.

Some typical values of the parameters needed in step 1 for a water-saturated, stainless-steel felt wick on a flat plate model are given in the following:

$$\epsilon = 0.5-0.9$$

$$\delta = 0.20-0.12 \text{ in.}$$

$$\nu = 10^{-5} \text{ ft}^2/\text{sec}$$

$$K = 1.88 \times 10^8 \text{ ft}^{-2} \quad (\text{manufacturer's data for "Feltmetal"})$$

$$\alpha = 3.22 \times 10^{-6} \text{ ft}^2/\text{sec} *$$

$$x_d \cong 2-20 \text{ in.}$$

$$z^* \cong 3-12 \text{ in. [4]}$$

* Accounting for the combined thermal conductivities of the solid and liquid as prescribed in ref. 7.

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$$c = 1 \text{ Btu/lb}_m\text{-}^\circ\text{F}$$

$$t_p - t_v = 0\text{-}30 \text{ }^\circ\text{F}$$

$$e_{v-\ell} = .970 \text{ Btu/lb}_m$$

$$t_o - t_v = -5\text{-}0 \text{ }^\circ\text{F}$$

$$G = \epsilon^2 \delta^2 g / g_c v^2 = 372\text{-}2.61 \times 10^5$$

$$K = \delta^2 \epsilon^2 K = 130\text{-}1.52 \times 10^4$$

$$Pr = \nu / \alpha = 3.1$$

$$T_o = (t_o - t_v) / (t_p - t_v) = -1.6\text{-}0$$

$$X_d = x_b / \delta = 32\text{-}320$$

$$Z^* = z^* / \delta = 25\text{-}600$$

$$\theta = 0\text{-}90^\circ$$

$$\Delta T = 10^{-5}\text{-}10^{-4}$$

$$n = 20\text{-}40$$

$$m = 10\text{-}20$$

$$E = c(t_p - t_v) / e_{\ell-v} = 0\text{-}.03$$

$$Q = q_p \delta c / k e_{\ell-v} = 0\text{-}.03$$

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EXPERIMENTAL APPROACH

The most convenient type of tests one can perform with the flat plate model is the constant temperature surface condition. Using a particular wick and liquid, different levels of T_0 , X_0 , Z_0 and $\mathcal{E}$ can be created so that data can be acquired for determining resulting values of Nu and X_d . These results can then be compared to the results of the numerical calculations previously described. Additional data can be acquired by simply changing the liquid in the experiment which gives new values of Pr and G . A new series of tests at different levels of T_0 , X_0 , Z_0 and $\mathcal{E}$ can then be performed. In order to change $\mathcal{K}$, a different wick must be installed.

If the experimental measurements of Nu agree reasonably well with those determined from the theoretical approach, then it can be concluded the theory is adequate for further predictions. If there is not good agreement, then either the theory must be revised until it does agree, or enough tests must be made with the experiment to adequately describe the effects of all the variables. It seems that the former is the best approach.

A requirement for good agreement between theory and experiment is accurate values of the properties must be known. Those that are difficult to obtain are the permeability parameter $\mathcal{K}$ and limiting pressure parameter Z^* . Special tests separate from the heat transfer experiments might have to be performed to determine them.

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SUMMARY

There are evidently nine dimensionless parameters, occurring in descriptive differential equations and boundary conditions, which control the performance of the flat plate model of a heated, liquid-saturated wick, namely, G , K , Pr , T_0 , X_0 , Z_0 , Z^* , θ and E or Q . The effect of these parameters on local heat transfer rates and location of wick "dry-up" can probably be determined by a prescribed numerical solution of the differential equations and experimental measurements from the same model. Results of the experiment can be compared to the theory to determine its accuracy. If there is agreement, then additional results can be computed from the theory.

An important condition the theory does not predict is the amount of superheat the liquid in the wick can withstand. At some limit, vapor will form in the wick blocking liquid flow and thus reduce the efficiency of heat transfer. Whether or not this vapor formation will make the wick stop working completely is not known. Conditions that cause vapor to form are probably like those that effect nucleation in pool boiling, e.g., surface condition, contaminants, nucleation sites, etc. Therefore, even the superheat limit observed in a particular experiment can not be consistently repeated in other experiments.

Another condition the theory does not predict is the shape of the "dry-up" boundary, i.e., whether it is a definite plane or numerous spots in the wick. Observed wick experiments indicate the former occurs.

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REFERENCES

1. K. T. Feldman, Jr. and G. H. Whiting, "The Heat Pipe," Mechanical Engineering, V89 n2, 1967, pp 30-33.
2. R. B. Bird, W. E. Stewart, E. N. Lightfoot, *Transport Phenomena*, John Wiley and Sons, New York, 1960, p 150.
3. F. W. Sears and M. W. Zemansky, *University Physics*, Addison-Wesley Publishing Co., Reading, Mass., 1955, p 235.
4. H. R. Kunz, et. al., "Vapor-Chamber Fin Studies," NASA CR-812, Pratt and Whitney Aircraft, West Hartford, Conn., June 1967, p 22.
5. H. Z. Barakat and J. A. Clark, "Anal. and Expt. Study of Trans. Lam. Nat. Conv. Flows in Part. Filled Liq. Containers," Proc. Int. Heat Trans. Conf., August, 1966, Vol II, pp 152-162.
6. R. J. Seeger and G. Temple, *Research Frontiers in Fluid Dynamics*, Interscience Publishers, New York, 1965, p 98.
7. R. G. Deissler and C. S. Eian, "Investigation of Effective Thermal Conductivities of Powders," NACA RM E52C05, Lewis Laboratory, Celveland, Ohio, 1952, p 44.

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