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A study of porous membrane evaporation for desalination in a flow system

Jing Ming Lee

A STUDY OF POROUS MEMBRANE EVAPORATION

FOR

DESALINATION IN A FLOW SYSTEM

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A

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M. E. Findley (advisor) Frank H. Conrad

S J Pagano

ABSTRACT

The purpose of this investigation was to study the simultaneous mass and heat transfer mechanism in evaporation through a porous membrane with a non-wettable surface. Such water repellent membranes permit the passage of water vapor, but not liquid water. The investigation concerned the mass transfer rate through the membrane pores with flow on one or both sides of the membrane.

The water-repellent membrane separated a hot salt solution from the fresh water, and a copper sheet separated the fresh water from a cold salt solution. A three-channel evaporator-condenser was used, and the membrane consisted of glass fiber paper treated with a teflon dispersion. The temperature range studied was from 93 to 190°F.

A temperature difference and a corresponding vapor pressure difference maintained across the membrane provided the driving force both for mass and heat transfer through the membrane and heat recovered through the copper sheet to cold salt solution. Theoretical and empirical correlations were employed to fit the experimental data. It was observed that heat transfer resistance and diffusion in the membrane pores were the major resistances to total mass transfer. The correlation predicted rates of mass transfer resistance close to the experimental values. The heat transfer coefficient was affected by the mass diffusion. The ratio of heat transfer coefficient with diffusion to that without diffusion was 1.5, and was slightly dependent on flow.

The mass transfer coefficient varied from 0.22 to 0.516 lb/(hr)(ft^2)(in-Hg). The overall heat transfer coefficient for

the membrane varied from 48 to 104 BTU/(hr(ft^2)(°F), and the overall heat transfer coefficient for the copper sheet varied from 54 to 84 BTU/(hr)(ft^2)(°F).

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

Ar = Transfer area of the membrane and copper sheet, ft^2.

b = Thickness of the membrane, ft.

C = Total molar density, lb-mole/ft^3.

C_{AF} = Pure water concentration, (lb-mole)/ft^3.

C_{AS} = Molar concentration of water in the hot salt solution, lb-mole/ft^3.

D_{AB} = Binary gas diffusion constant, diffusivity, ft^2/hr.

DW = Amount of water transferred to the fresh water side from the hot salt solution, lb/hr.

DPM = Log mean vapor pressure, in-Hg.

E = Boiling point elevation of the salt solution, °F.

F_1, F_2
F_3, F_4 = Correlation equation functions.

G = Mass flow rate, lb/(hr)(ft^2).

h = Film heat transfer coefficient, BTU/(hr)(ft^2)(°F).

h_F = Film heat transfer coefficient of fresh water, BTU/(hr)(ft^2)(°F).

h_R = Film heat transfer coefficient of cold salt solution (recovery side), BTU/(hr)(ft^2)(°F).

h_S = Film heat transfer coefficient of hot salt solution, BTU/(hr)(ft^2)(°F).

k = Thermal conductivity, BTU/(hr)(ft)(°F).

k_c = Thermal conductivity of copper sheet, BTU/(hr)(ft)(°F).

k_e = Thermal conductivity of the membrane, BTU/(hr)(ft)(°F).

K_M = Overall mass transfer coefficient, lb/(hr)(ft^2)(in-Hg).

M_A = Molecular weight of component A.

M_B = Molecular weight of component B.

N_A = Mass flux of component A, (lb-mole)/(hr)(ft^2) or lb/(hr)(ft^2).

p = Total pressure of the system, (in-Hg).

p_{A1} = Vapor pressure at the membrane surface on hot salt solution side, (in-Hg).

p_{A2} = Vapor pressure at the membrane surface on fresh water side, (in-Hg).

p_{AF} = Vapor pressure of the fresh water at the bulk temperature, (in-Hg).

p_{AS} = Vapor pressure of the hot salt solution at the bulk temperature (in-Hg).

Δp_m = Log mean partial pressure difference of the water vapor, (in-Hg).

Q = Heat flux.

q_c = Conduction heat through the membrane.

q_{c1} = Total heat transferred from the hot salt solution to fresh water.

q_{c2} = Total heat transferred from fresh water to cold salt solution as recovery heat.

q_{L1} = Heat loss from the hot salt solution channel.

q_{L2} = Heat loss from the fresh water channel.

q_{L3} = Heat loss from the cold salt solution channel.

q_R = Total heat recovered by cold salt solution.

q_t = Total heat input to the system.

q_v = Heat content in the vapor.

R = Gas constant

T = Absolute temperature, °R.

$\overline{T}$ = Average absolute temperature in the membrane, °R.

ΔT_m = Log mean temperature difference.

TFM = Average temperature of fresh water channel, °F.

TM1 = Average temperature at the membrane surface on hot salt solution side, °F.

TM2 = Average temperature at the membrane surface on fresh water side, °F.

TRI = Cold salt solution inlet temperature in the tube, °F.

TRM = Average temperature of the cold salt solution channel, °F.

TRO = Cold salt solution channel outlet temperature in the tube, °F.

TSI = Hot salt solution inlet temperature in the tube, °F.

TSM = Average temperature of the hot salt solution channel, °F.

TSO = Hot salt solution channel outlet temperature in the tube, °F.

U_c = Overall heat transfer coefficient for the copper sheet, BTU/(hr)(ft^2)(°F)

U_m = Overall heat transfer coefficient for the membrane.

U_3 = Heat transfer coefficient by conduction through the membrane, BTU/(hr)(ft^2)(°F)

W_S = Circulation flow rate, lb/hr.

X = Mole fraction.

Z = Diffusion direction and path, ft.

Subscripts:

A, B, referring to water vapor and air, respectively.

1, 2, referring to positions of salt water and fresh water membrane surface, respectively.

S, F, referring to salt water and fresh water, respectively.

I. INTRODUCTION

Membrane transfer phenomena and theory has been studied for over a hundred years in biological systems. However, the potential of the application of membranes in engineering has been developed only in recent years (10). One recent method of evaporation through porous membranes has been proposed by Findley (4). This method, applied to the conversion of sea water to fresh water, is the subject of this investigation.

Membrane desalination processes have the potential advantages of economical operating costs, and simple equipment. The method studied in this investigation requires only a suitable porous membrane to separate the hot salt solution and the coolant fresh water and heat exchange equipment to supply and recover heat.

The salt solution at a higher temperature has a higher water vapor pressure than the vapor pressure of fresh water at a little lower temperature. The higher vapor pressure will produce diffusion through the membrane pores to the coolant fresh water which serves as a vapor condenser. The surface tension (5) keeps the fresh water from entering the pores. With counter-current flow, each pore is at a different temperature and functions as a single stage of flash evaporation. Thus, a porous membrane can provide an infinite number of stages of flash evaporation. Flash evaporation refers to evaporation from sensible heat in this paper.

Before this process can be applied to industrial production, it is necessary to thoroughly understand the relationship of the heat and mass transfer. Previous studies (7, 13, 14, 19) provided some useful information on this method, but further study of this process is still required, primarily to establish the effects of flow on the transfer relationship.

The purpose of this work was to study evaporation through the porous membranes in a flow system in order to determine the relationships of flow to heat and mass transfer.

II. THEORY AND LITERATURE REVIEW

This chapter is to discuss the theory and mechanism associated with the simultaneous heat and mass transfer through a water repellent porous membrane with a temperature gradient to provide the driving force for both heat and mass transfer.

A. Theory of Heat Transfer

1. Conduction

Fourier's law applied to one-dimensional heat transfer by conduction is,

$$Q = -k \frac{dT}{dZ} \tag{2-1}$$

Q = heat flux, BTU/(hr)(ft^2)(°F)

k = conductivity, BTU/(hr)(ft)(°F)

T = temperature, °F

Z = thickness of the transfer path and direction, ft.

2. Convection

There are two types of convection, one is natural (or free) convection due to density differences without external force, another is forced convection due to a pressure drop which causes turbulence in the fluid flowing. Convection is accompanied by a transfer of heat by conduction. Most liquid, and nearly all gases conduct heat so poorly that the heat transferred by conduction is, in general, negligible compared to that heat transferred by convection (15).

In this study with laminar flow, both natural and forced convection and possibly liquid conduction could be important. The conventional concept of heat transfer film coefficient is given by the equation,

$$Q = h(T_w - T_b) = h\Delta T \qquad (2\text{-}2)$$

h = film heat transfer coefficient, BTU/(hr)(ft^2)(°F)

ΔT = the temperature difference between the surface of the wall and the bulk temperature of the fluid, °F.

3. Radiation

Since temperature differences are small, radiation was assumed negligible in this study.

B. Mass Transfer

1. Diffusion in Binary System

Fick's law of diffusion with concentration gradients is similar to Fourier's law of heat conduction applied to diffusion in a binary system in one-dimensional diffusion. Fick's law is (1),

$$N_A = -CD_{AB} \frac{\partial XA}{\partial Z} + X_A \, (N_A + N_B) \qquad (2\text{-}3)$$

where

N_A, N_B = molar flux of A and B respectively

X_A = mole fraction of A

C = total molar density

D_{AB} = diffusivity, ft^2/hr

Z = diffusion path and direction, ft.

This equation shows that molar flux N_A is the result of two vector quantities, one of which is the bulk flow term $X_A(N_A + N_B)$, and the other is the diffusion term $CD_{AB}\frac{\partial XA}{\partial Z}$.

If a system is at steady state with constant molar flux equation 2-3 can be applied directly, but we must know the relation of N_A and N_B, C and D_{AB} in order to solve the equation. Fuller, Schettler and Giddings (6), gave an equation for a diffusion coefficient in gases as follows,

$$D_{AB} = K\frac{\overline{T}^{1.75}}{p(V_A^{1/3} - V_B^{1/3})}\left(\frac{1}{M_A} + \frac{1}{M_B}\right)^{1/2} \qquad (2\text{-}4)$$

V_A, V_B = molecular volume of A and B respectively.

M_A, M_B = molecular weight of A and B respectively

K = a constant for a pair of gases

$\overline{T}$ = average absolute temperature of the system, °R

p = total pressure of the system, in-Hg

The equation shows that D_{AB} is independent of concentration and dependent on total pressure and temperature. It is reasonable to assume that D_{AB} is a constant in a system with small changes of temperature and constant pressure.

C. Simultaneous Heat and Mass Transfer in Porous Membrane Desalination

1. Mass Transfer Through the Membrane

In this desalination process the temperature gradient produce partial pressure gradients across the pores of the membrane (see Fig. 2-1), and at any given temperature there is a corresponding partial pressure of the water vapor whether vapor is present or not.

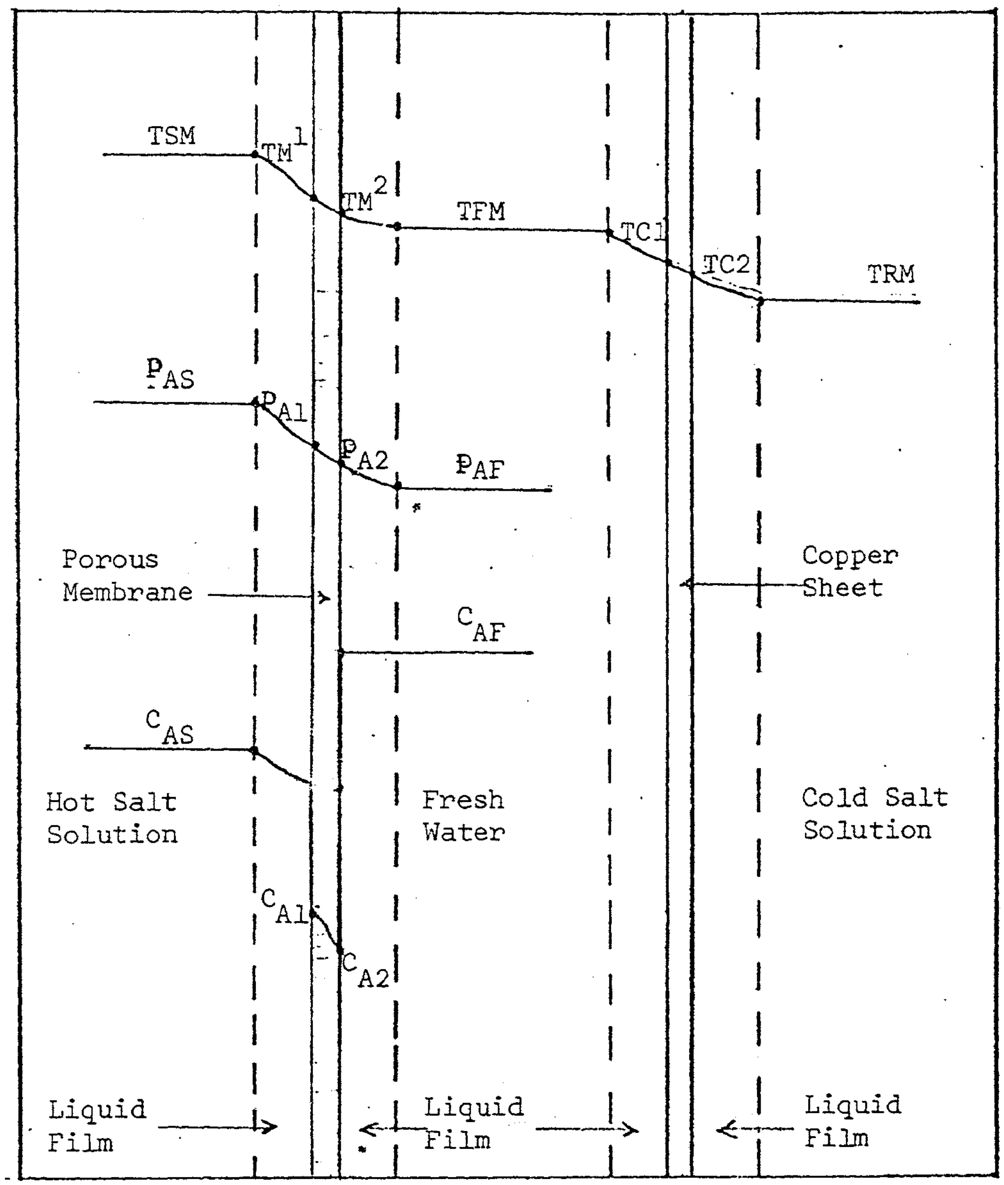

Figure 2-1. Temperature, partial pressure and concentration profile in the membrane condenser system.

TSM, TFM, TRM = bulk mean temperatures, refer to hot salt, fresh and cold salt water respectively.

TM1, TM2 = surface temperatures of the membrane, refer to hot salt and fresh water.

TC1, TC2 = surface temperatures of copper sheet, refer to fresh and cold salt water.

C_{AS}, C_{AF} = concentration of water in the hot salt water and pure water.

C_{A1}, C_{A2} = concentration of water in the vapor at the membrane interfaces.

P_{AS}, P_{AF} = equilibrium vapor pressures at TSM and TFM

P_{A1}, P_{A2} = equilibrium vapor pressure of water at the interface of the membrane at TM1 and TM2.

The higher partial pressure of water vapor on the hot side provides a driving force for diffusion through a stagnant air film in the membrane pores with condensation occurring at the other cooler side of the membrane. Therefore, for the flux of air, $N_B=0$, and by applying equation 2-3 (2),

$$N_A = -CD_{AB} \left(\frac{1}{1-X_A}\right) \frac{\partial XA}{\partial Z} \qquad (2\text{-}5)$$

For a steady state using equation 2-4 and combining constants,

$$D_{AB} = k'\overline{T}^{\,1.75}$$

For moderate temperature and atmospheric pressure, the ideal gas law can be applied.

$$C = p/R\overline{T}$$

so,

$$CD_{AB} = \frac{P}{R\overline{T}} \; k'\overline{T}^{1.75} = k_D \; \overline{T}^{0.75} \tag{2-6}$$

For moderate temperature change we can assume CD_{AB} is a constant, and since the flux is constant through its transfer path, N_A is a constant and we get from equation 2-5,

$$\frac{d}{dZ}\left[\left(\frac{1}{1-XA}\right)\left(\frac{\partial XA}{\partial Z}\right)\right] = 0$$

Integration with boundary conditions as follows,

$Z = Z1 = 0 \qquad X = X_{A1}$

$Z = Z2 = b \qquad X = X_{A2}$

We get (2),

$$\left(\frac{1-X_A}{1-X_{A1}}\right) = \left(\frac{1-X_{A2}}{1-X_{A1}}\right)^{Z/b} \tag{2-7}$$

X_A, X_B = mole fraction of A and B respectively.

X_{A1}, X_{A2} = mole fraction of A at each interface of the membrane respectively.

b = thickness of the membrane, ft.

Equation 2-7 gives the concentration profile of the diffusion path in the membrane pores. A combination of equation 2-5 and 2-7 gives,

$$N_A = \frac{CD_{AB}}{b} \ln \frac{X_{B2}}{X_{B1}} = \frac{CD_{AB}}{b} \frac{X_{B2} - X_{B1}}{(X_B)_{Lm}} \tag{2-8}$$

where

$$(X_B)_{Lm} = (X_{B2} - X_{B1})/(\ln \frac{X_{B2}}{X_{B1}})$$

$$X_{B2} = 1 - X_{A2}$$

$$X_{B1} = 1 - X_{A1}$$

If the concentration is represented by partial pressure of the water vapor, equation 2-8 becomes,

$$N_A = \frac{P}{R\overline{T}} \cdot \frac{D_{AB}}{b} \ln \frac{p_{B2}}{p_{B1}} = \frac{pD_{AB}}{bR\overline{T}} \frac{p_{A1} - p_{A2}}{(\bar{p}_B)_{Lm}} \tag{2-9}$$

since $C = p/R\overline{T}$

where

$$(p_B)_{Lm} = \frac{p_{B2} - p_{B1}}{\ln(p_{B2}/p_{B1})}$$

Equation 2-9 shows that the rate of diffusion of gas A is directly proportional to the pressure difference between the interfaces, and inversely proportional to the length of the diffusion path and to the logarithmic mean partial pressure of the stagnant gas B in the path.

Since we do not know the temperature at each interface of the membrane, we do not know the corresponding vapor pressure p_{A1} and p_{A2}. For application of the equation, a mass transfer coefficient was defined for convenience (16).

$$\bar{N}_A = K_M (p_{AS} - p_{AF}) \tag{2-10}$$

K_M = overall mass transfer coefficient, lb/(hr)(ft^2)(in-Hg).

p_{AS}, p_{AF} = vapor pressure of the hot salt solution and fresh water at bulk temperatures respectively.

The two films concept was first suggested by W. G. Whiteman in 1923 (17), and has proved to be a great aid in understanding the process of diffusion between two fluids. We assume the interface of two phases on the surface of contact are in equilibrium and there is no appreciable diffusion resistance at the actual interface (18).

Then in this case all the resistance to the mass diffusion is present in the membrane pores and in the salt water film. For the rates encountered in this investigation, it was also assumed that the salt water film resistance was negligible compared to the resistance of the vapor phase in the pores.

2. Heat Transfer Coefficient

The main heat transfer resistance for a fluid, cooling or heating, depends on the fluid layer in contact with the heat transfer surface. The thickness of this boundary layer depends on internal motion of the fluid. A number of heat transfer coefficient correlations appear in the literature, Sieder and Tate derived the equation for laminar stream flow as follows (9),

$$\frac{hD}{k}\left(\frac{\mu_s}{\mu_b}\right)^{0.14} = 1.86\left[\left(\frac{DG}{\mu_b}\right)\left(\frac{Cp\mu}{k}\right)_b (D/L)\right]^{1/3}$$

For small temperature ranges $\mu_s/\mu_b = 1$

Then,

$$h = a\,\frac{k^{0.67}}{D^{0.33}}\left(\frac{CpG}{L}\right)^{0.33} = a\ f\ (G.T) \qquad (2\text{-}11)$$

where

a = constant.

a = 1.86 for cylindrical pipes

L = length of heat transfer area, ft.

K = thermal conductivity of the fluid.

C_p = heat capacity, BTU/(lb)(°F)

G = mass flow, lb/(hr)(ft^2)

D = diameter, ft.

$f(G.T) = (k^{0.67}/D^{0.33})(CpG/L)^{0.33}$

h = heat transfer coefficient, $BTU/(hr)(ft^2)(°F)$

Perry's handbook gives the following equation for natural convection (12),

$$h = 43 \left(\frac{\Delta T}{D}\right)^{0.25} = d f(\Delta T/D) \tag{2-12}$$

where

43 = constant for horizontal plate

d = constant

ΔT = temperature drop between the wall and the bulk temperature.

$f(\Delta T/D) = (\Delta T/D)^{0.25}$

3. Theoretical Correlation of Heat and Mass Transfer

First, heat must be transferred from the bulk of the stream of hot salt solution to the membrane interface, then the same amount of heat should also be transferred through the membrane by evaporation and conduction and again through the fresh water film to the bulk of the fresh water. The same mechanisms transferred heat to the recovery cold salt solution through two films and through a copper sheet by conduction (see Fig. 2-2).

Heat transfer through the copper sheet may be expressed as,

$$q_{C2} = U_c(TFM-TRM) \tag{2-13}$$

The resistances to heat transfer are:

$$1/U_c = 1/h_F + 1/h_R + x/k_c$$

U_c = overall heat transfer coefficient for the copper sheet, $BTU/(hr)(ft^2)(°F)$

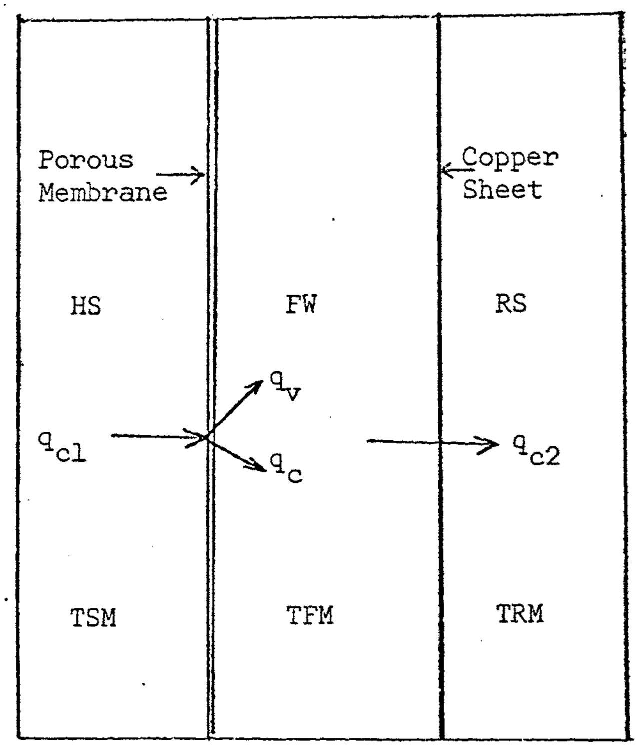

Figure 2-2. Heat transfer in the process.

q_v = heat carried by vapor

q_c = heat transferred through the membrane by conduction

q_{c1} = $q_v + q_c$ = total heat transferred from hot salt solution to the fresh water.

q_{c2} = total heat transferred from fresh water to cold salt solution (recovery heat)

TFM, TRM = bulk mean temperature of the fresh water and cold salt solution respectively

k_c = conductivity of the copper sheet, BTU/(hr)(ft)(°F)

X = thickness of the copper sheet, ft.

h_F, h_R = heat transfer coefficients referring to fresh and cold salt water respectively

Since X/k_c is very small and can be neglected, then

$$1/U_c = 1/h_F + 1/h_R \tag{2-14}$$

Heat balances over the membrane are as follows:

$$q_c = U_3(TSM-TFM) = \frac{k_e}{b}(TM1-TM2)$$

$$q_{c1} = h_S(TSM-TM1) = h_F(TM2-TFM)$$

Then

$$(TSM-TFM) - (TM1-TM2) = q_{c1}\left(\frac{1}{h_S} + \frac{1}{h_F}\right) \tag{2-15}$$

and

$$q_{c1} = q_v + q_c = N_A H + \frac{k_e}{b}(TM1-TM2) \tag{2-16}$$

Combining equations 2-15 and 2-16,

$$(TSM-TFM) = [N_A H + \frac{k_e}{b}(TM1-TM2)]\left(\frac{1}{h_S} + \frac{1}{h_F}\right) + (TM1-TM2) \tag{2-17}$$

where

TM1, TM2 = temperatures on the membrane surfaces of hot salt and fresh water side respectively

h_S = heat transfer coefficient of hot salt solution

k_e = effective conductivity of the membrane

U_3 = heat transfer coefficient across the membrane by conduction

TSM = bulk mean temperature of the hot salt solution, °F

For moderate ΔT across the membrane, we assume the vapor pressure is linear relation with temperature at atmospheric pressure (see Fig. 2-3), and assumed $P_{AS}+P_{AF} \doteq P_{A1}+P_{A2}$.

Therefore,

$$TM1-TM2 = \frac{TSM-TFM}{p_{AS}-p_{AF}} (p_{A1}-p_{A2}) \qquad (2\text{-}18)$$

By expansion of equation 2-8 (21),

$$N_A = \frac{CD_{AB}}{b} (\ln X_{B2} - \ln X_{B1})$$

$$X_{B2} = 1 - X_{A2} = 1 - (p_{A2}/p)$$

$$X_{B1} = 1 - X_{A1} = 1 - (p_{A1}/p)$$

$$N_A = \frac{CD_{AB}}{b} [\frac{1}{p} (p_{A1}-p_{A2}) + \frac{1}{2p^2} (p_{A1}^2 - p_{A2}^2) + \frac{1}{3p^3} (p_{A1}^3 - p_{A2}^3) + \ldots]$$

Taking the first two terms and combining with equation 2-6, we get

$$p_{A1} - p_{A2} = \frac{b}{k_D} \frac{N_A}{\overline{T}^{0.75}(1 + \frac{p_{AS} + p_{AF}}{2p})} \qquad (2\text{-}19)$$

A combination of equations 2-18 and 2-19 gives,

$$(TM1-TM2) = \frac{TSM-TFM}{p_{AS}-p_{AF}} \frac{b}{k_D} \frac{2p^2}{\overline{T}^{0.75}(2p+p_{AS}+p_{AF})}$$

We should consider the tortuous diffusion path (3) and the effective diffusion area of the membrane. Therefore, the thickness b should

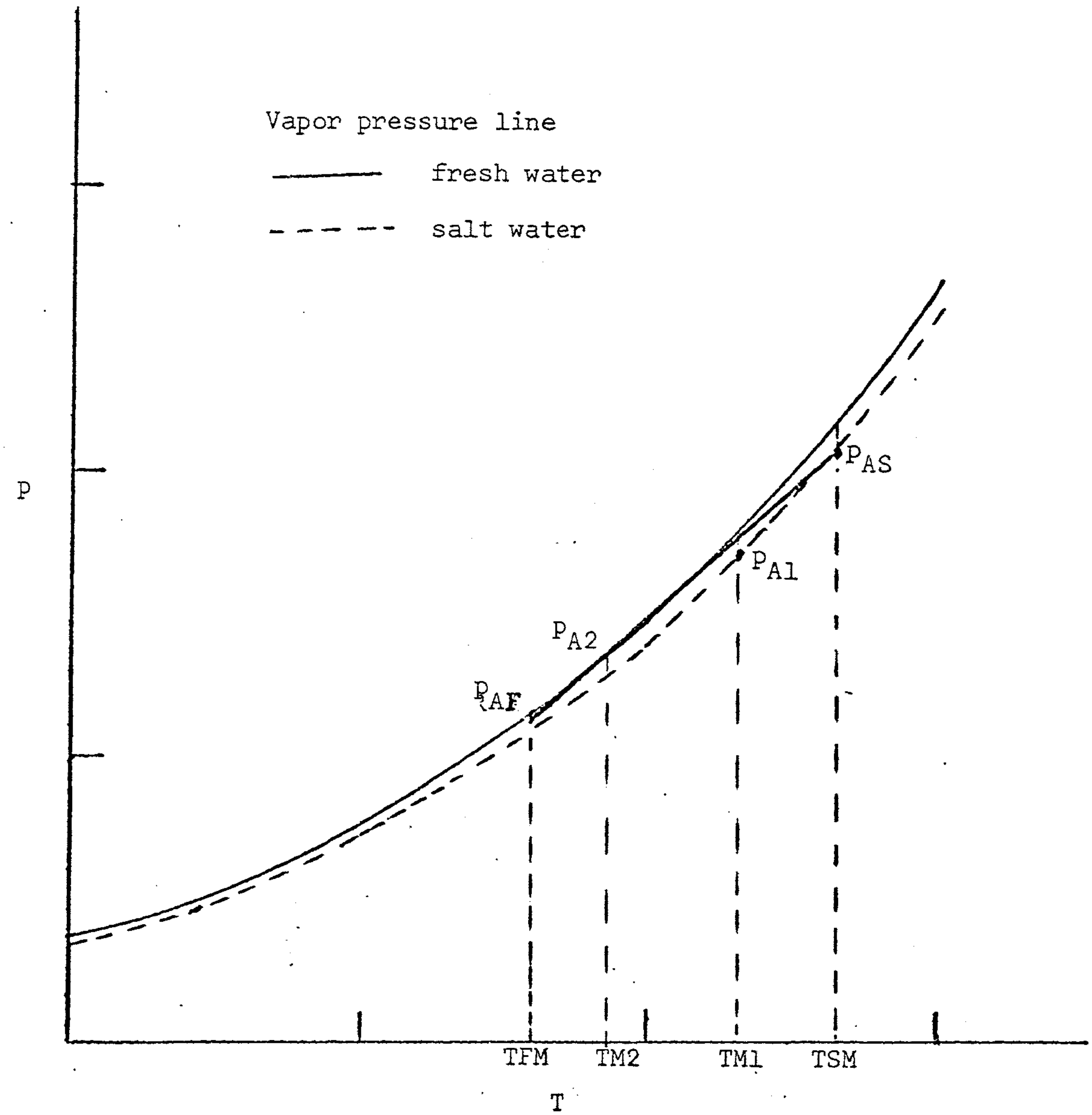

Figure 2-3. Vapor pressure versus temperature showing fluid and membrane conditions.

be multiplied by 1.414 to correct for tortuousity (3). The diffusion constant k_D, should be multiplied by void fraction of the membrane to correct for the effective area of diffusion. Then,

$$(TM1-TM2) = \frac{(TSM-TFM)}{(p_{AS}-p_{AF})} \quad \frac{b \cdot 1.414}{k_D \; po} \quad \frac{2p^2 \; N_A}{\bar{T}^{0.75}(2p+p_{AS}+p_{AF})} \tag{2-20}$$

where

po = porosity of the membrane, or void fraction

Substitute equation 2-20 into equation 2-17 and combine with equation 2-10, then

$$\frac{1}{K_M} = \frac{(p_{AS}-p_{AF})H}{(TSM-TFM)} \left(\frac{1}{h_S} + \frac{1}{h_F}\right) + \frac{k_e}{k_D} \quad \frac{2p^2 1.414}{po \; \bar{T}^{0.75}(2p+p_{AS}+p_{AF})}$$

$$\left(\frac{1}{h_S} + \frac{1}{h_F}\right) + \frac{b}{k_D} \quad \frac{2p^2 1.414}{po \; \bar{T}^{0.75}(2p+p_{AS}+p_{AF})} \tag{2-21}$$

The first term is equivalent to the film resistance associated with the heat of vaporation and condensation. The third term is the resistance to diffusion in the membrane and the second term is an effect of membrane heat conduction parallel to mass transfer of the liquid film. For flow systems mean ΔP and ΔT are used.

$$\text{Let } (p_{AS} - p_{AF}) = (\Delta p)_{Lm} \tag{2-22}$$

$$(TSM - TFM) = (\Delta T)_{Lm} \tag{2-23}$$

$$\frac{2p^2 \cdot 1.414}{po \; \bar{T}^{0.75}(2p+p_{AS}+p_{AF})} = P_P \tag{2-24}$$

Then equation 2-21 becomes

$$\frac{1}{K_M} = \frac{(\Delta p)_{Lm} H}{(\Delta T)_{Lm}} \left(\frac{1}{h_S} + \frac{1}{h_F}\right) + \frac{k_e}{k_D} P_P \left(\frac{1}{h_S} + \frac{1}{h_F}\right) + \frac{b}{k_D} P_P \tag{2-25}$$

Where

$$(\Delta p)_{Lm} = \frac{(p_{SI}-p_{FO}) - (p_{SO}-p_{FI})}{\ln \left(\frac{p_{SI} - p_{FO}}{p_{SO} - p_{FI}}\right)}$$

$$(\Delta T)_{Lm} = \frac{(T_{SI}-T_{FO}) - (T_{SO}-T_{FI})}{\ln \left(\frac{T_{SI} - T_{FO}}{T_{SO} - T_{FI}}\right)}$$

p_{SI}, p_{SO} = the vapor pressure of water on the hot salt solution side at the inlet and outlet ends of the channel respectively.

p_{FI}, p_{FO} = the vapor pressure of water on the fresh water side at the inlet and outlet ends of the channel respectively.

T_{SI}, T_{SO} = the hot salt solution temperature at inlet and outlet ends of the channel respectively.

T_{FI}, T_{FO} = the fresh water temperature at the inlet and outlet ends of the channel respectively.

III. APPARATUS AND EXPERIMENTAL

A. Apparatus

A rectangular membrane Evaporator-Condenser was used in this investigation. The apparatus was made of acrylic plastic plate and consisted of three channels. The channel dimensions were 16.25" x 1.5" x 0.5" at both sides and 16.25" x 1.5" x 0.6" at the middle (see Fig. 3-1). Two zenith metering pumps running at the same speed maintained the circulation. The mass transfer area was 0.1695 ft^2. Ten copper-constantan thermocouples were used to measure the desired temperature (see Appendix for details).

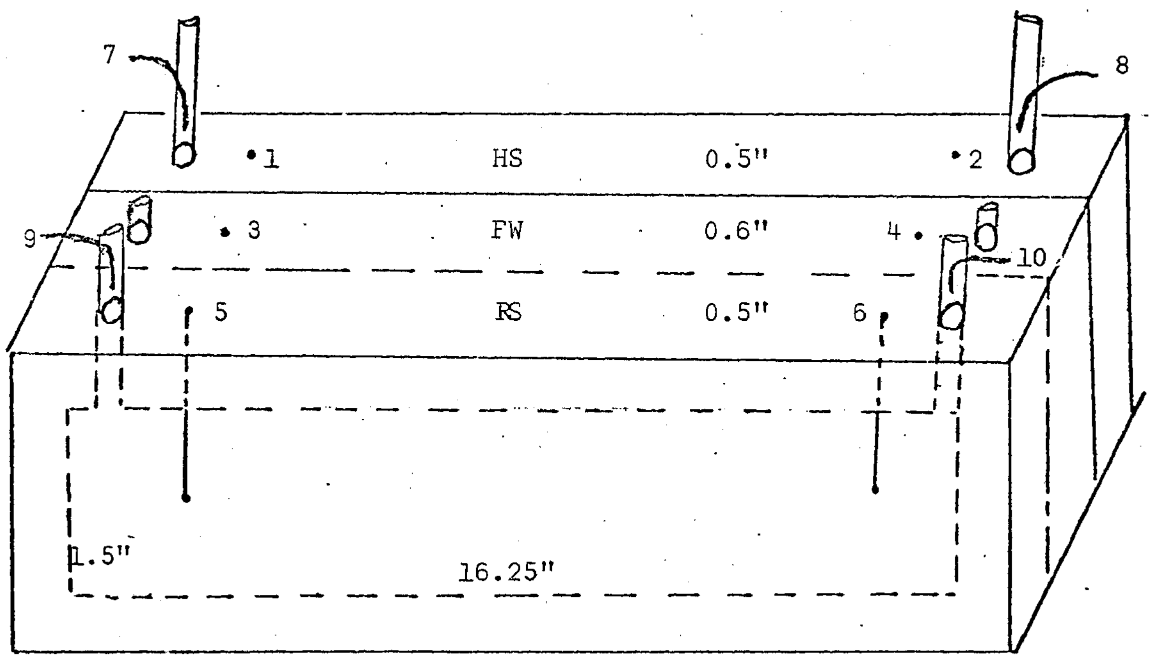

Figure 3-1. The Evaporator-Condenser.

Where

HS = hot salt solution channel

FW = fresh water channel

RS = heat recovery section, cold salt solution channel

1, 2, 3, 4, 5, 6 = thermocouples measuring the channel temperatures

7, 8, 9, 10 = thermocouples measuring the solution inlet and outlet temperatures (EMF) in the inlet and outlet tubes

B. Experimental

The procedure in brief was to assemble and connect the equipment of the system, to switch on motor-pumps, and to heat up the salt solution with a heated copper coil connecting the cold salt solution outlet to the hot salt solution inlet. After temperatures and level were steady, data were taken of time, temperature, amount of water transferred, flow rate and room temperature every 10 to 30 minutes (for details see Appendix, page 40).

C. Method of Calculation

Experimental data were used to calculate the following: 1) The overall mass transfer coefficient, K_M; and 2) The overall heat transfer coefficients, U_M, U_c and U_3.

U_M is the overall heat transfer coefficient for the membrane.

U_c is the overall heat transfer coefficient for the copper sheet.

U_3 is the heat transfer coefficient for the membrane by conduction.

Figure 3-2 shows the heat and mass balance in the evaporator-condenser.

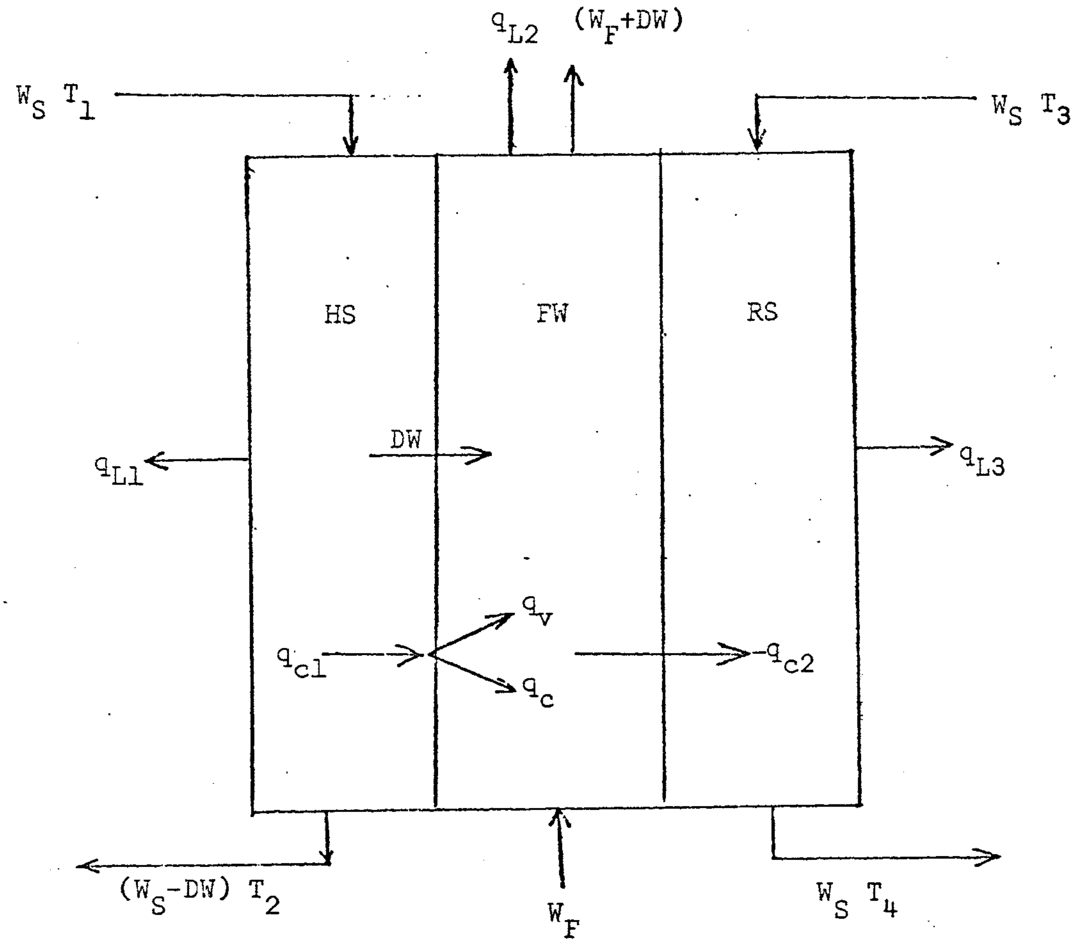

Figure 3-2. Heat and mass flow in the evaporator-condenser.

Where

q_{L1}, q_{L2}, and q_{L3} are the heat losses in each channel based on the area exposed to the air, and temperature differences with the outside air.

T_1, T_2 = hot salt solution temperatures at inlet and outlet tubes respectively, °F.

T_3, T_4 = cold salt solution temperatures at inlet and outlet tubes respectively, °F.

W_S, W_F = the mass flow rate in lb/hr of salt solution and fresh water respectively.

DW = the amount of water transferred from the salt solution to the fresh water side, lb/hr.

TSM, TFM, TRM = the mean bulk temperatures of the fluids and refer to hot salt solution, fresh water and cold salt solution respectively.

The calculation of the mean bulk temperature of the fluids was as follows:

$$TSM = [T_{SI}(N) + T_{SI}(N+1) + T_{SO}(N) + T_{SO}(N+1)]/4$$

$$TFM = [T_{FI}(N) + T_{FI}(N+1) + T_{FO}(N) + T_{FO}(N+1)]/4$$

$$TRM = [T_{RI}(N) + T_{RI}(N+1) + T_{RO}(N) + T_{RO}(N+1)]/4$$

Where

N = the subscript referring to the measuring order according to time.

T_{SI}, T_{SO} = the hot salt solution temperature at inlet and outlet ends of the channel.

T_{FI}, T_{FO} = the fresh water temperature at the inlet and outlet ends of the channel.

T_{RI}, T_{RO} = the cold salt water temperature at the inlet and outlet ends of the channel.

For enthalpy loss on the hot salt solution side, q_t

$$q_t = W_S(T_1-32) - (W_S-DW)(T_2-32)$$

Where 32°F is the enthalpy reference temperature and specific heat = 1.0.

$$q_{cl} = q_t-q_{Ll} = q_v+q_c = N_AH + \frac{k_e}{b}(TM1-TM2)$$

$$U_m = \frac{q_{c1}}{Ar(TSM-TFM)} = \frac{q_{c1}}{Ar(\Delta T)_{LM}} \tag{3-1}$$

where

Ar = the heat and mass transfer area, ft^2

H = the vapor enthalpy, BTU/lb

U_m = overall heat transfer coefficient for the membrane

The enthalpy increase on the recovery side, q_R, may be calculated as

$$q_R = W_S(T_4-T_3)$$

The total heat transferred through the copper sheet should include the heat loss, q_{L3}, therefore

$$q_{c2} = q_R + q_{L3}$$

This was the amount of heat transferred from the fresh water to the cold salt solution. Then

$$U_c = \frac{q_{c2}}{Ar(TFM-TRM)} \tag{3-2}$$

where

U_c = overall heat transfer coefficient for the copper sheet.

For heat conduction through the membrane,

$$U_3 = \frac{q_c}{Ar(TSM-TFM)} = \frac{q_c}{Ar(\Delta T)_{LM}} \tag{3-3}$$

where

$$(\Delta T)_{LM} = \frac{(T_{SI}-T_{FO}) - (T_{SO}-T_{FI})}{\ln \dfrac{T_{SI} - T_{FO}}{T_{SO} - T_{FI}}}$$

T_{SI}, T_{SO} = hot salt solution bulk temperatures at the inlet and outlet channel ends.

T_{FI}, T_{FO} = fresh water bulk temperature at the inlet and outlet channel ends.

For mass transfer as defined in equation 2-10, it was assumed that

$$K_M = \frac{N_A}{(p_{AS}-p_{AF})} = \frac{DW}{Ar(\Delta p)_{LM}} \tag{3-4}$$

where

$$(\Delta p)_{LM} = \frac{(p_{SI}-p_{FO}) - (p_{SO}-p_{FI})}{\ln \frac{(p_{SI} - p_{FO})}{(p_{SO} - p_{FI})}}$$

p_{SI}, p_{SO} = the vapor pressure of the hot solution at the inlet and outlet channel ends.

p_{FI}, p_{FO} = the vapor pressure of the fresh water at the inlet and outlet channel ends.

Calculations of the salt solution vapor pressure and pure water vapor pressure are made as follows.

$$a. = (f_s/f_f)_T = (p_S/p_F)_T$$

a. = activity of water in solution

f_s = fugacity of water in salt solution

f_f = fugacity of pure water

T = temperature, °F

For small temperature changes and constant concentration in the system, the activity a. is approximately constant and equal to 0.96 (21).

Therefore,

$$p_S = 0.96 \times p_F$$

where,

p_S = vapor pressure of salt solution

p_F = vapor pressure of pure water

The vapor pressure of pure water is obtained from the following equation (8):

$$\log_{10} \frac{p_c}{p} = \frac{x}{T} \left(\frac{a' + b'x + c'x^3}{1 + d'x} \right)$$

where

p = vapor pressure in atm

p_c = 218.167 atm

$T = t^{o}C + 273.16$, absolute temperature

$x = T_c - T$

T_c = 647.27

a' = 3.2437814

$b' = 5.86826 \times 10^{-3}$

$c' = 1.1702379 \times 10^{-8}$

$d' = 2.1878462 \times 10^{-3}$

D. Data and Results

All the data and results are tabulated in the Appendix from page 47 to 64.

IV. DISCUSSION

A. System with Both Salt and Fresh Water Flowing

The hot salt water, fresh water and cold salt water are in countercurrent flow with adjacent stream in the system.

1. Correlation

From equation 2-25 and 2-11,

$$\frac{1}{K_M} = \frac{1}{a}\ \frac{(\Delta p)_{LM}\ H}{(\Delta T)_{LM}}\ \left(\frac{1}{f(G.T)_S} + \frac{1}{f(G.T)_F}\right) + \frac{k_e}{k_D a}$$

$$p_p\ \left(\frac{1}{f(G.T)_S} + \frac{1}{f(G.T)_F}\right) + \frac{b}{k_D}\ \cdot\ p_p \qquad (4\text{-}1)$$

a, k_e, k_D are assumed approximately constants. Yeh (22) found molecular diffusion to be the rate controlling factor for mass transfer in the membrane. The same molecular diffusion was assumed in this study and the other constants were evaluated by the least squares method. The least squares equation for the high flow rate (96 cc/min to 210 cc/min) data is as follows,

$$F1 = \frac{1}{K_M} = 0.0683\ \frac{(\Delta p)_{LM} H}{(\Delta T)_{LM}}\ \left(\frac{1}{f(G.T\ )_S} + \frac{1}{f(G.T\ )_F}\right) + 13.4\ p_p$$

$$\left(\frac{1}{f(G.T\ )_S} + \frac{1}{f(G.T\ )_F}\right) + 2540\ b\ p_p \qquad (4\text{-}2)$$

A plot was made of $1/K_M$ versus function F1 (see Fig. 4-1). In evaluating the constants, unreasonable results were obtained when using low flow rate (42 cc/min to 96 cc/min) data. For example, the mean of temperatures measured in the hot salt water channel were almost equal or slightly below measured outlet temperatures in the tube, which is impossible if the temperatures represent the

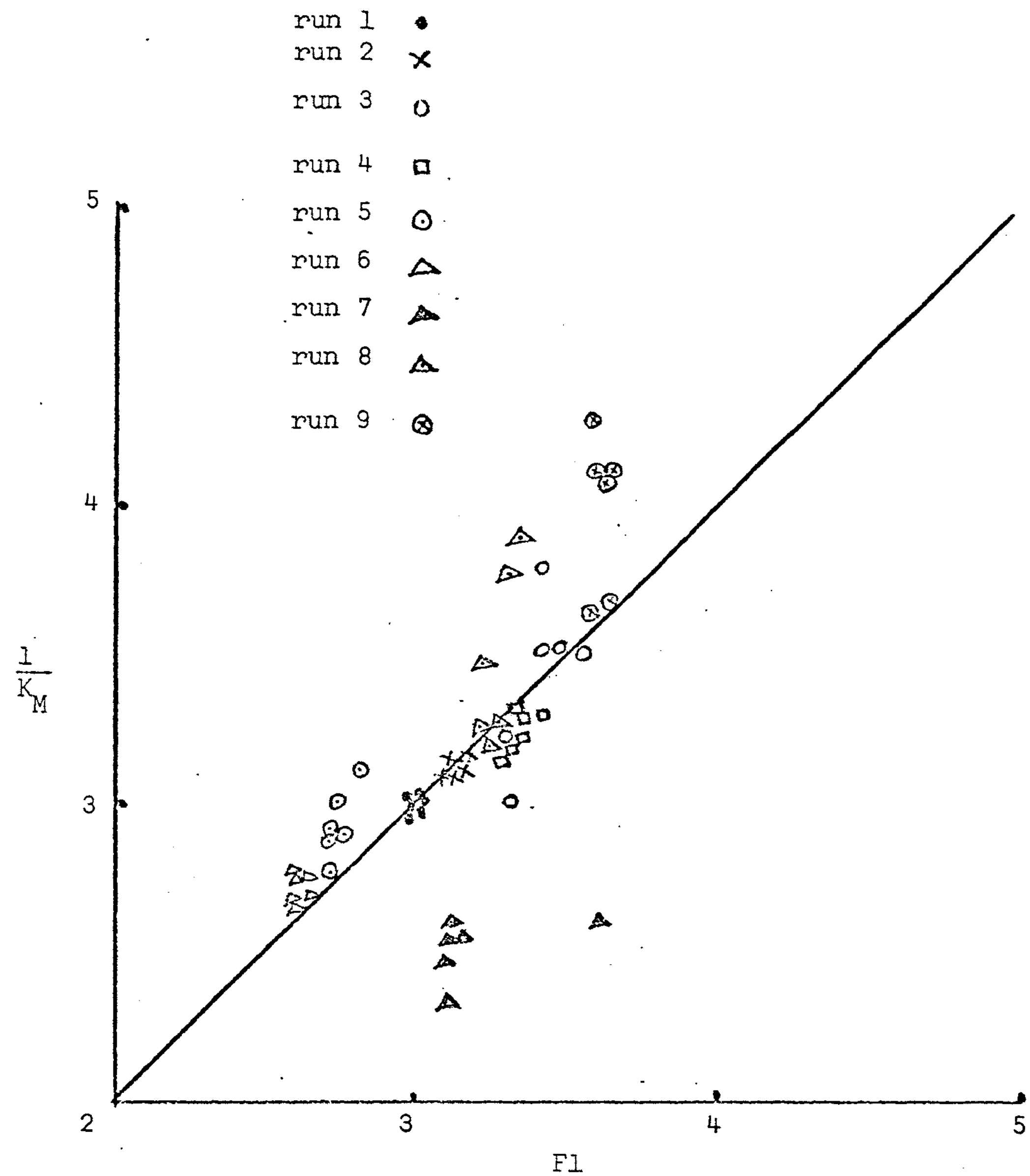

Figure 4-1. Experimental $1/K_M$ versus Function Fl.

$$\mathrm{Fl} = \frac{1}{K_M} = 0.0683\ \frac{(\Delta p)_{Lm} H}{(\Delta T)_{Lm}} \left(\frac{1}{f(G.T.)_S} + \frac{1}{f(G.T)_F}\right)$$

$$+\ 13.4\ p_p \left(\frac{1}{f(G.T\ )_S} + \frac{1}{f(G.T)_F}\right) + 2540\ b\ p_p$$

true conditions. This indicates the flows are non-uniform, probably with higher temperature liquids channeling in the upper part of the chambers. For high flow rate data the temperatures were more reasonable and predicted relationships were consistent with the experimental results. For the above reasons the low flow rate data were not used in the correlations.

Comparing equation 4-1 with equation 4-2, where the constant $1/k_D = 2540$ is a theoretical value at 32°F and atmospheric pressure, a and k_e can be obtained from the least squares coefficients in equation 4-2. The constants determined in this way are a=14.65, k_e=0.0775.

The heat transfer coefficient is around 250 BTU/(hr)(ft^2)(°F), which is reasonable in the heat transfer range for a laminar flow system. The effective k_e, is the conductivity of the solid phase and vapor phase of the membrane. Actually k_e is a variable with solid phase fraction and vapor phase composition, however, the changes are small. The calculated k_e, is 0.057 to 0.058, but this calculation did not consider the convection heat transfer of the vapor. However this convection in the membrane is very small. Other factors are thickness of the membrane which is not uniform, and any effects of moisture in the membrane. Therefore, it is reasonable for calculated k_e, 0.0775, from least squares coefficient to be larger than the theoretical value of k_e, 0.057 to 0.058.

The constant a=14.65, is considerably larger than the value found in the literature, 1.86. However, this constant depends on internal flow, and equipment geometry, and the value in the literature is for round tubes whereas this study was made using rectangular channels.

Rao (13) pointed out that boiling point elevation has a strong effect on overall mass transfer resistance. A parameter was added to equation 4-1, to determine whether such a term would improve the correlation. The equation became,

$$F2 = \frac{1}{K_M} = 0.065 \frac{(\Delta p)_{Lm} H}{(\Delta T)_{Lm}} \left(\frac{1}{f(G.T.)_S} + \frac{1}{f(G.T.)_F}\right) + 1.9\ pp$$

$$\cdot \left(\frac{1}{f(G.T)_S} + \frac{1}{f(G.T)_F}\right) + 2540 \times b\ p_p$$

$$+ 7761 \frac{[((\Delta T)_{Lm} - E)b]}{\overline{T}} \qquad (4\text{-}3)$$

Where E is boiling point elevation for 7% salt water, 1.4°F. A plot was made of $1/K_M$ versus function F2 given in equation 4-3. The predicted values of equation 4-3 were closer to the experimental values (see Fig. 4-2), but this did not appear to justify the strong effect on the second term of the equation 4-3 and 4-2. Further studies of the effect of ΔT seem to be desirable.

2. Heat Transfer

For heat conduction through the membrane, the equation for heat transfer is as follows.

$$q_c = U_3(TSM-TFM) = \frac{k_e}{b}(TM1-TM2)$$

$$k_e = \frac{U_3\ b\ (TSM-TFM)}{(TM1-TM2)} = \frac{U_3\ b\ (\Delta T)_{Lm}}{(TM1-TM2)}$$

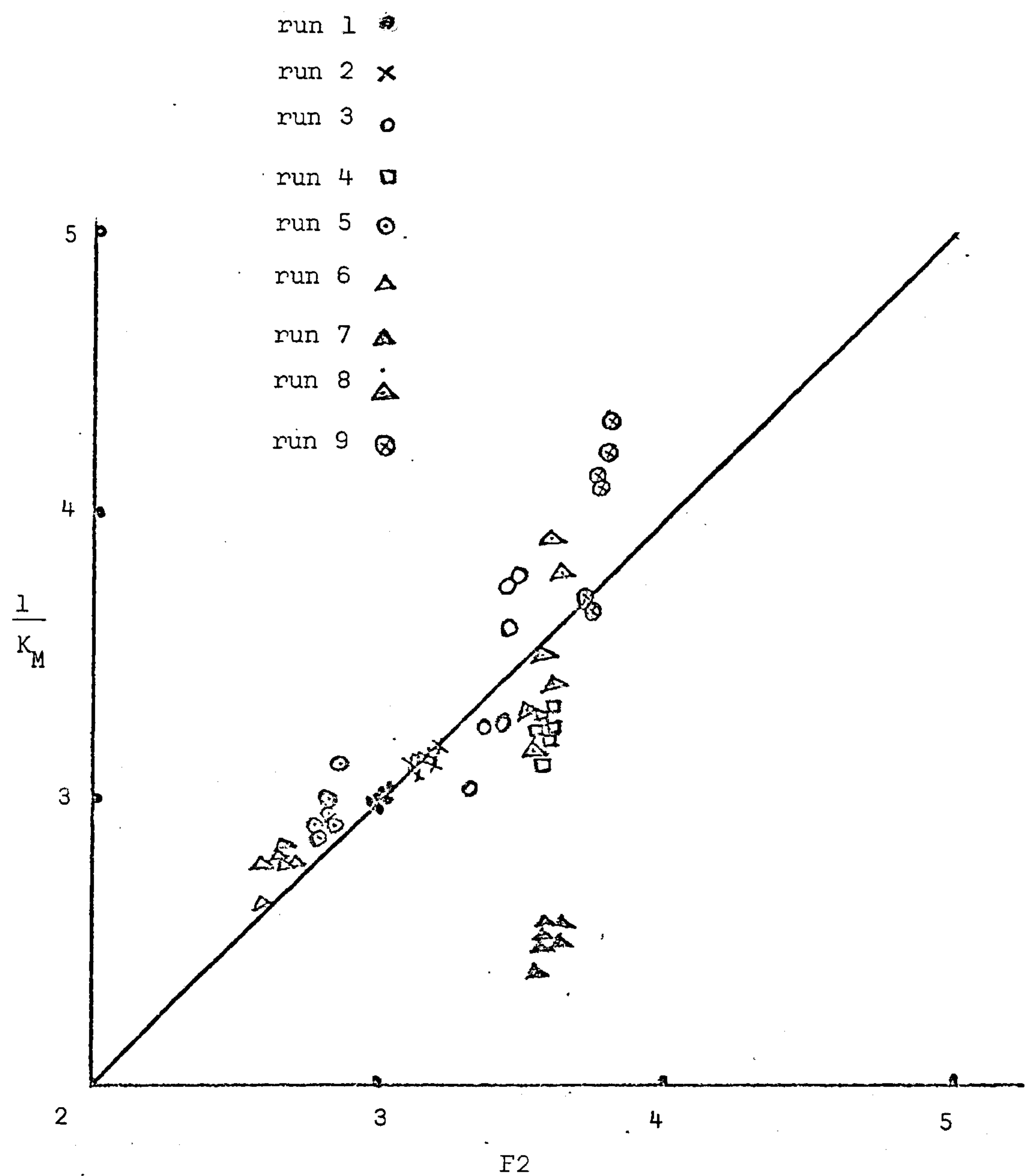

Figure 4-2. Experimental $1/K_M$ versus F2.

$$F2 = \frac{1}{K_M} = 0.065 \frac{(\Delta p)_{Lm} H}{(\Delta T)_{Lm}} \left(\frac{1}{f(G.T)_S} + \frac{1}{f(G.T)_F}\right) + 1.9 \, p_p$$

$$\cdot \left(\frac{1}{f(G.T)_S} + \frac{1}{f(G.T)_F}\right) + 2540 \, b \, p_p + 7761 \frac{[(\Delta T)_{Lm} - E)b]}{\overline{T}}$$

Combining with equations 2-20 and 2-10,

$$k_e = \frac{U_3}{\left[\frac{1}{k_D} \quad \frac{2p^2 \cdot 1.414 \; K_M}{T^{0.75}(2p+p_{AS}+p_{AF})po}\right]} \qquad (4\text{-}4)$$

$$= \frac{U_3}{(2540 \; p_p \; K_M)}$$

The average k_e, of each set of data is as follows,

run 1 = 0.072

run 2 = 0.064

run 3 = 0.059

run 4 = 0.059

run 5 = 0.062

run 6 = 0.075

run 7 = 0.064

run 8 = 0.083

run 9 = 0.061

Since the latent heat of water is very high, a small error in the measurement of the transferred water would introduce a large error in U_3. However, the value of k_e obtained from equation 4-4 is reasonably close to the value calculated by least squares, 0.0775.

For heat transfer coefficient for the copper sheet, we can obtain from equation 2-14 and 2-11,

$$\frac{1}{U_c} = \frac{1}{h_F} + \frac{1}{h_R} = \frac{1}{a'f(G.T)_F} + \frac{1}{a'f(G.T)_R}$$

a' = a constant

By analysis of experimental results,

$$F3 = U_c = \frac{9.5f(G.T)_F \times f(G.T)_R}{f(G.T)_F \times f(G.T)_R} \tag{4-5}$$

Thus the constant a'=9.5. A plot of U_c versus F3 is shown in Figure 4-3.

Comparing the constants obtained for the membrane and the copper sheet, a/a'=1.5. This factor is believed to be due to the effect of the mass diffusion at the membrane surfaces on the film coefficient.

B. System with No Fresh Water Flowing

1. Empirical Correlation

In the case where there is no fresh water flow, the heat transfer coefficient of fresh water is by natural convection, and is proportional to a power of (TM2-TFM). For convenience, it was assumed that (TM2-TFM) was proportional to (TSM-TFM)/2.

Then from equation 3-25, combined with equations 2-11 and 2-12,

$$\frac{1}{K_M} = \frac{1}{a} \frac{(\Delta p)_{Lm} H}{(\Delta T)_{Lm}} \frac{1}{f(G.T)_S} + \frac{1}{d} \frac{(\Delta p)_{Lm} H}{(\Delta T)_{Lm}} \frac{1}{f(\Delta T/D)_F} + \frac{k_e}{k_D a} P_P$$

$$\cdot \frac{1}{f(G.T)_S} + \frac{k_e}{k_D d} \cdot P_P \cdot \frac{1}{f(\Delta T/D)_F} + \frac{b}{k_D} \cdot P_P \tag{4-6}$$

From the previous analysis the constants k_e, a, k_D were known and the constant d was evaluated and found to be d=52.6, when high flow rate data were used.

The equation 4-6 became as follows:

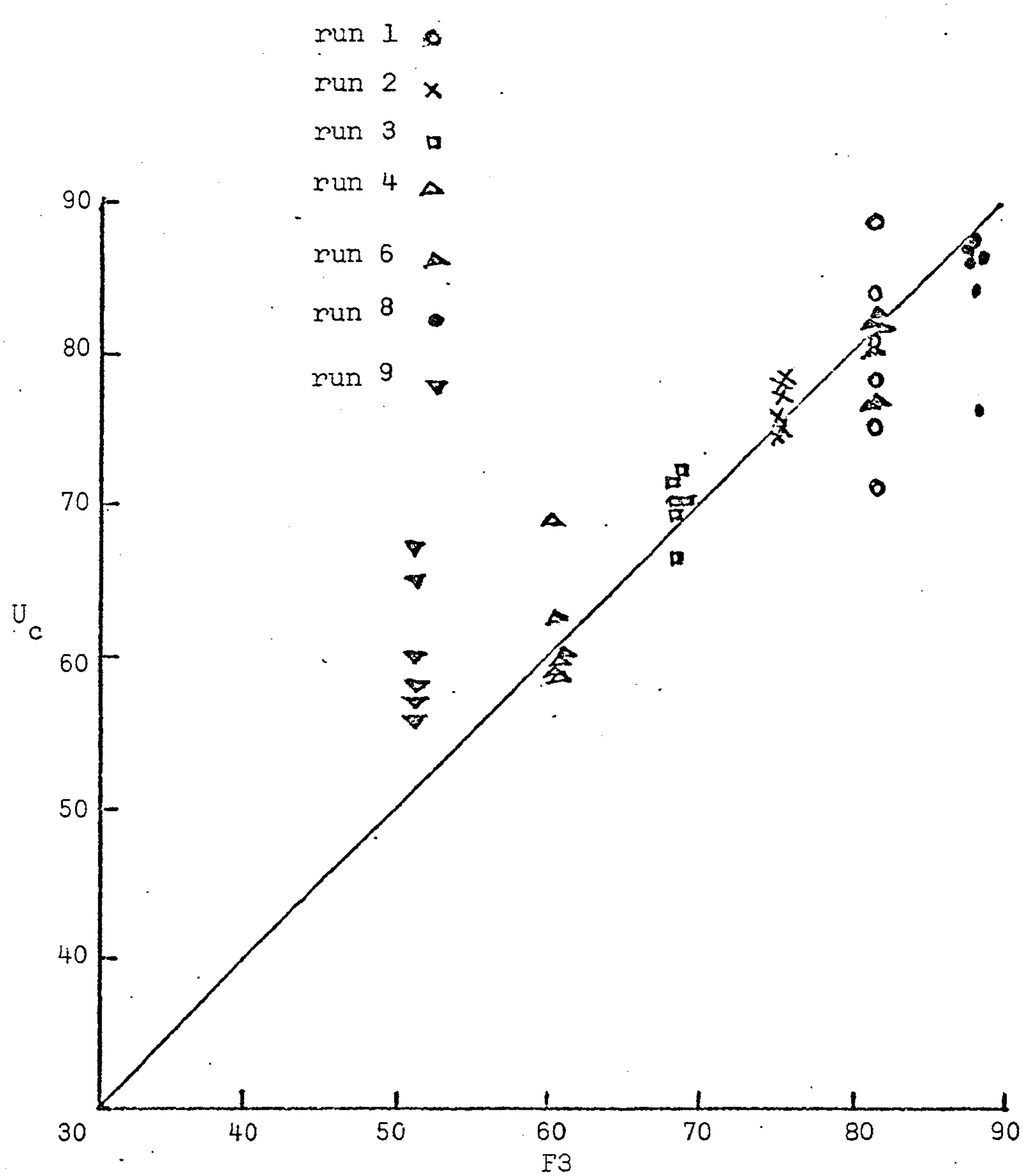

Figure 4-3. Experimental U_c versus function F3.

$$F3 = U_c = \frac{9.5f(G.T)_F \cdot f(G.T)_R}{f(G.T)_F + f(G.T)_R}$$

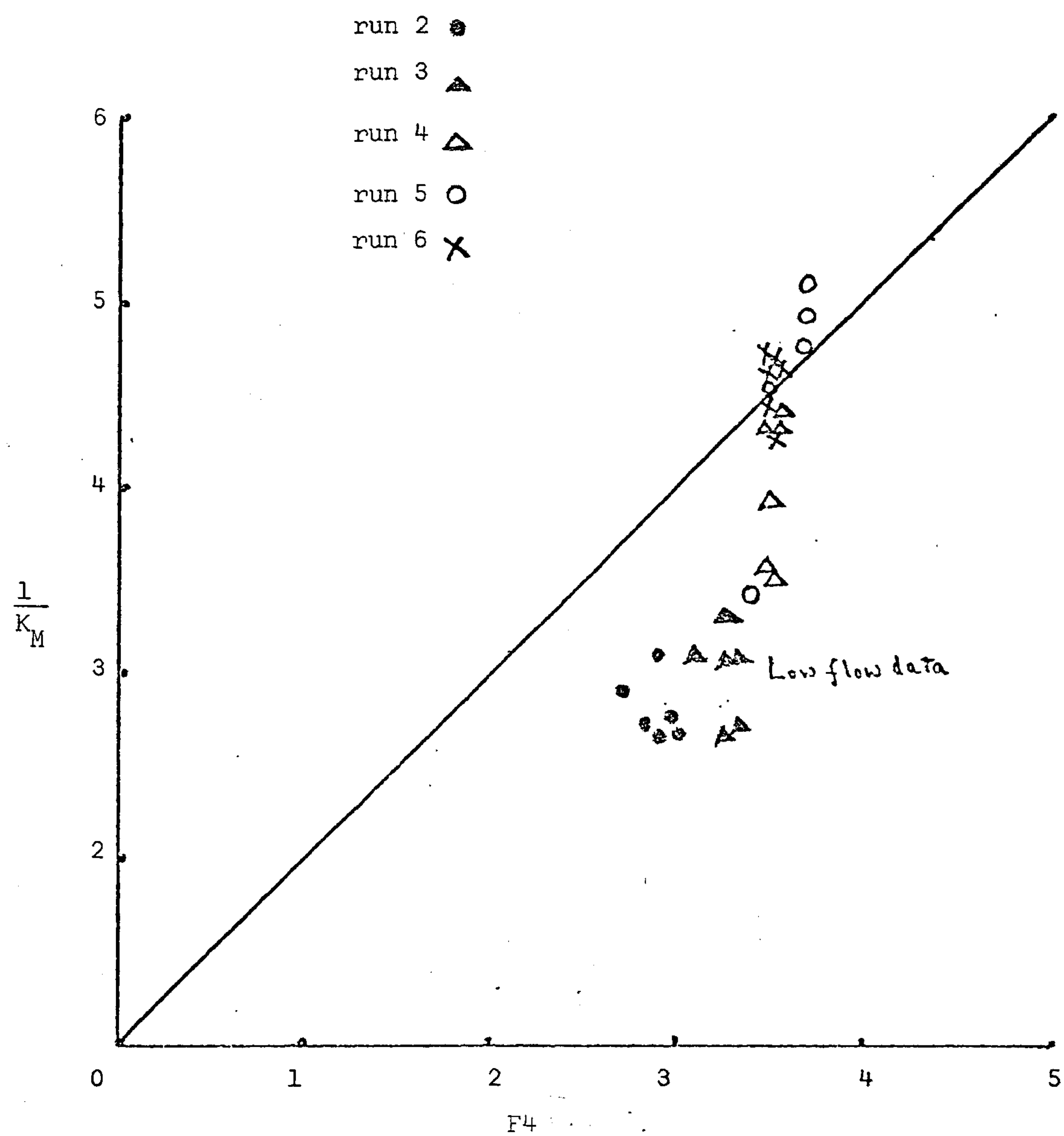

Figure 4-4. Experimental $1/K_M$ versus function F4.

$$F4 = \frac{1}{K_M} = 0.0683 \frac{(\Delta p)_{Lm} H}{(\Delta T)_{Lm}} \frac{1}{f(G.T)_S} + 0.019 \frac{(\Delta p)_{Lm} H}{(\Delta T)_{Lm}} \cdot \frac{1}{f(\Delta T/D)_F}$$

$$+ 13.4 \, p_p \frac{1}{f(G.T)_S} + 3.74 \, p_p \frac{1}{f(G.T)_F} + 2540 \, b \, p_p$$

$$F4 = \frac{1}{K_M} = 0.0683 \frac{(\Delta p)_{Lm} H}{(\Delta T)_{Lm}} \frac{1}{f(G.T)_S} + 0.019 \frac{(\Delta p)_{Lm} H}{(\Delta T)_{Lm}} \frac{1}{f(\Delta T/D)_F}$$

$$+ 13.4 \; p_p \frac{1}{f(G.T)_S} + 3.74 \; p_p \frac{1}{f(\Delta T/D)_F} + 2540 \; b \; p_p \qquad (4.7)$$

Comparing d of equation 4-6, with the literature value of 43, the ratio is about 1.2. Since (TSM-TFM)/2 is a little larger than the value of (TM2-TFM), this ratio would also be close to 1.5 if true film ΔT values were used.

In Figure 4-4, all low flow rate (below 131 cc/min flow) data will not fit the equation 4-7, and were all lower than the predicted value of F4. This could be explained, for low flow, if the detected temperatures were lower than actual temperatures in the channel as discussed previously. However, the temperature of fresh water was probably more uniform because of no flow. Therefore, the measured TSM-TFM would be smaller than the actual value and TFM-TRM would be greater than the actual value. Possibly for this reason a higher U_m, k_m, U_3 and a lower U_c were obtained (As shown in Results in the Appendix, from page 56 to 64). For both fluids flowing, the deviations of temperatures occur on both sides in the same direction. Therefore, the differences of temperatures are probably more reliable with both fluids flowing. However, there would be some effect on vapor pressure, p_{AS} and p_{AF}, but this effect should not be large.

2. Heat Transfer

The heat transfer with no fresh water flow was not correlated because of suspected incorrect temperatures.

V. CONCLUSION

The following conclusions have been obtained from the data and results during the investigation.

1. Mass transfer through the membrane is by diffusion.
2. The overall mass transfer resistance is the sum of three terms in theoretical equation 2-25. The first term is proportional to heat transfer resistance associated with evaporation and condensation at both sides of the membrane. The second term is due to the parallel heat conduction through the membrane and is small compared to other two. The third term is diffusion resistance in the membrane.
3. The heat transfer coefficient in the liquid films is affected by flow rate in the expected manner, and also appears to be affected by the mass diffusion.

VI. RECOMMENDATIONS

If this membrane process is to be applied in industrial desalination further studies of this process are recommended. The following studies are believed to be the most important.

1. A high flow rate study of this process at atmospheric pressure should be made.
2. The process should be studied as near the boiling point as possible in order to decrease the existance of non-condensable gases in the membrane pores.
3. Better membrane qualities should be investigated.
4. Further studies appear to be desirable on the effect of ΔT across the membrane.
5. The diffusion resistance in liquid films and the effect of liquid diffusion on heat transfer coefficient should also be studied.

VII. APPENDICES

A. Apparatus

The apparatus was made of Acrylic plastic plate. It consisted of three parallel channels. The two outside channels were 1.5 inches in height and 16.25 inches long. Both exterior channels were 0.5 inch thick. The center channel was 0.6 inch in thickness. A membrane separated hot salt solution which flowed in one exterior channel from fresh water flowing in the middle channel. A copper sheet in turn separated the fresh water from cold salt solution flowing in the other exterior channel.

The circulation of the salt solution and fresh water was provided by two Zenith metering pumps running at the same speed. A speed controller on a Zero-Max drive power block, could be adjusted to the desired flow rate from 0 to 210 cc/min. The power was supplied by a 1/6 horse-power AC motor.

The energy required for evaporation was provided by a gas burner which heated the cold salt solution, which flowed through a water bath coil, to a desired temperature before it entered the hot salt solution chamber of the evaporator-condenser. Ten thermocouples were used to measure the temperatures. One was placed at each end of each of the three channels, another four were placed in the inlet and outlet tubes of the salt solution channels. The apparatus used 1/4 inch copper and plastic tubing and suitable fittings, so that a closed liquid circulation system could be maintained.

B. Equipment

1. Evaporator-Condenser Gaskets

The channels of the evaporator-condenser were sealed by rubber gaskets.

2. Liquid Reservoirs

Two one gallon containers (plastic) were used as reservoirs for salt and fresh water. Each was connected to the pump inlet line with a 1/4 inch plastic tube and valve.

3. Level Guage Tubes

Two 5/8 inch glass tubes 15 cm long were used as level indicators. They were connected to the pump suction line at the bottom (see Fig. App. 1).

4. Heater

A copper coil in a stainless steel container 10 inches in depth served as a water bath and a gas burner supplied the heat.

5. Thermocouples

Ten copper-constantan thermocouples made from size 20 A.W.G. wire, were used to measure the inlet and outlet temperatures of the channel fluid. One was fixed in the middle of each channel entrance and exit. The other four were fixed in the inlet and outlet tubes of hot and cold salt solutions.

6. Potentiometer

A potentiometer (Indicator, portable, model No. 1324, by the Winslow Company, Inc.) was used to measure the EMF of each thermocouple, for conversion to temperature units.

7. Motor and Pumps

Two Zenith metering pumps were used to maintain the circulation of fluids. The pumps were driven by a Zero-Max drive power block, model EL. The energy was supplied by a Zero-Max motor model M2, 1/6 horse-power, 115 v, 725 RPM.

8. Graduated Cylinder

A 25 milliliter graduated cylinder was used to collect the amount of water transferred.

9. Miscellaneous

Copper and plastic tubing and fittings were used for connecting the system. A glass disk and electric oven were used in making the membrane.

C. Materials

The materials used in this investigation are listed below.

1. Membrane

A purchased glass fiber filter paper (Grade 934AH, H. Reeve Angel and Co.) 6"x18", was used for preparing membrane.

2. Teflon Solution

E. I. Dupont's Teflon 30-B dispersion was used for making the membrane. It is an aqueous dispersion containing 59 to 61 percent solids. It has a density of 1.5 g/cc, a pH of 10 and a viscosity of 15 centipoise at room temperature. The density of Teflon solids is 2.2 g/cc and thermal conductivity is 0.625 BTU/(hr)(ft)(°F).

3. Condensate Water

Steam condensate from a condensate line was used to prepare the salt solutions and to serve as fresh water.

4. Salt

Industrial grade salt (NaCl) was used for preparing 7% by weight salt solution.

5. Silver Nitrate

Reagent grade silver nitrate was used to detect any Cl^- ion present in the condensate.

D. Procedures

1. Membrane Preparation

The glass fiber paper (6"x10") was dipped in an aqueous Teflon dispersion (about 3 cc of Teflon 30-B mixed with 40 cc of water), then dried over night at room temperature. The membrane was then heated in an oven at 500°F for 30 minutes. After drying in the oven, drops of fresh water were placed on the membrane surfaces to check the water repellent character of the membrane. Any unsatisfactory membranes, those which absorbed water or became wet on the surface, were discarded. The membrane in the apparatus had a transfer area of 0.1695 ft^2 with a void fraction of about 0.9 and a thickness of 0.019 inches.

2. Experimental Procedure (see Fig. App. 1)

The first step was to assemble the evaporator-condenser and tighten it with bolts. The circulation line in the system was then connected and each reservoir was filled with salt and fresh water accordingly. The reservoir valves were opened to the pump suction line, and the motor was started while both discharge line drain valves were open (S2, F2). Any dirt in the pump was flushed out, then valve S2 was closed, and salt solution entered the recovery section. After salt solution over flowed from the exit, valve F2 was closed. The salt solution and fresh water entered each side of the membrane at the same volumetric rate to prevent rupturing the membrane due to unbalance of pressure. After circulation for a while, the glass tubes had the same level as in the reservoirs. Then the make up valves, S1, F1, to the pump suction were closed, and the gas burner was started for heating up the system. After heating to the desired temperature, the vapor from the salt water began to transfer and gradually lowered the level in LS and increased the level in LF. Valve F5 was opened to let any transferred water flow to a graduated cylinder. Valve F3 was opened to the salt solution system to automatically make up the water loss and maintain constant concentration. After about two hours, a steady state was reached, and data of temperatures, time, flow and amount of water transferred could be taken.

Usually data readings were made once every 10 to 30 minutes. At least 7 sets of data were taken in each run and the flow was adjusted as desired.

For runs with no fresh water flow, the procedures were the same, except that after steady state flows were reached, the fresh water pump was disengaged from the driving great and the valve F4 was closed.

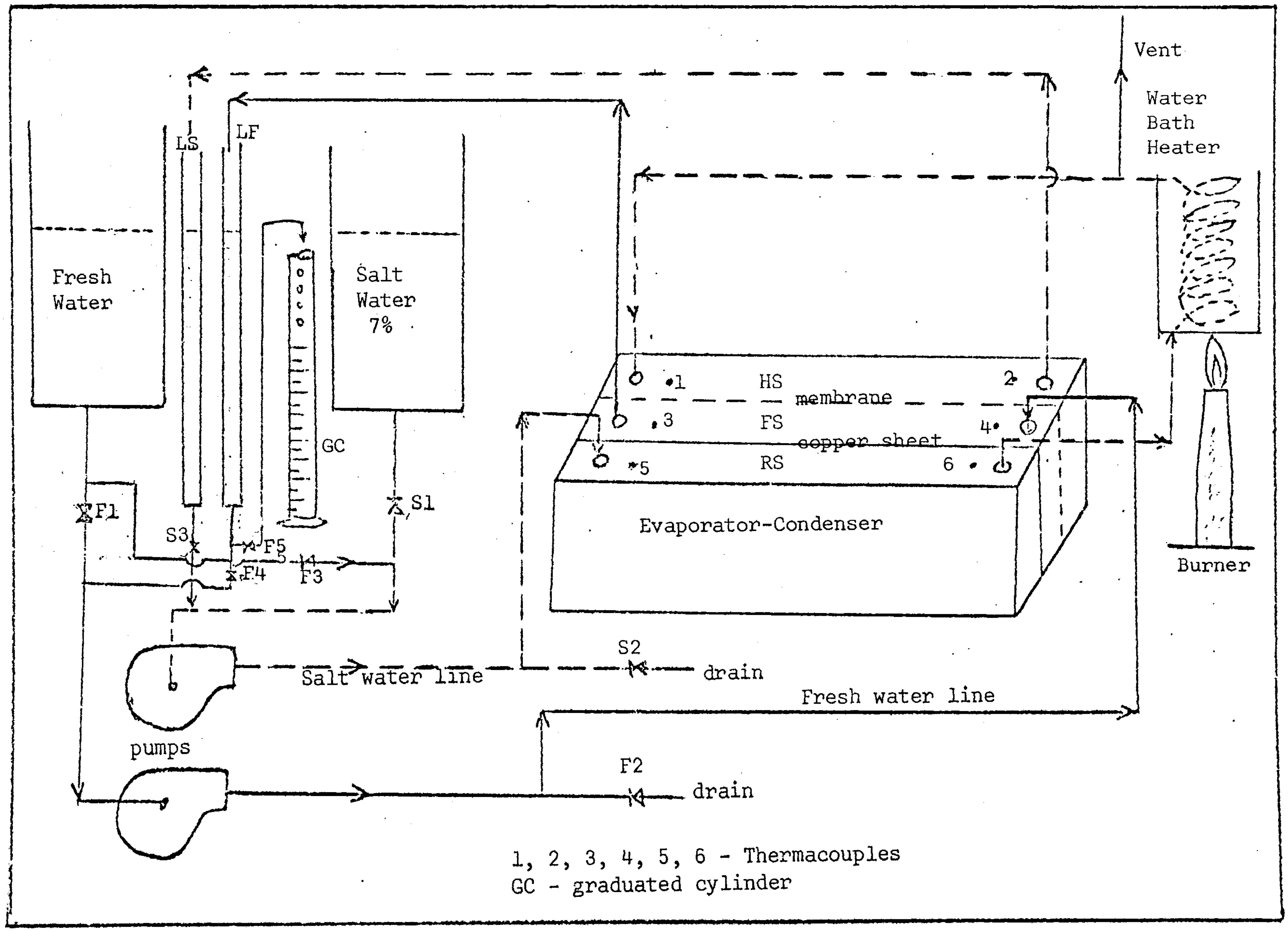

Figure App 1. Cycle flow diagram of experimental process.

E. Trouble Shooting

1. Temperatures

Before four extra thermocouples were added to the inlet and outlet tubes, a heat balance over the system was unreasonable, and negative heat transfer coefficients were obtained, similar to Hsu's work (6). It was found that the inlet and outlet tube temperatures were greatly different from the temperatures measured in each exit and inlet channel (see Fig. App 2).

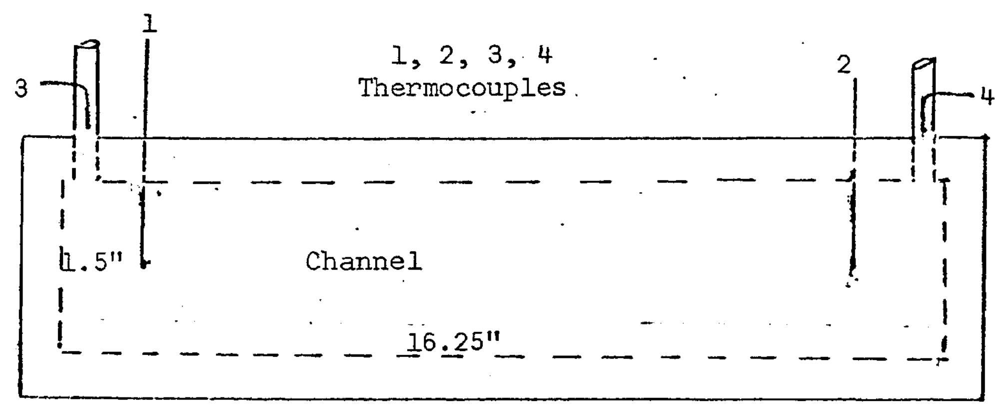

Figure App 2. The position of thermocouples in the channels and tubes.

After four thermocouples were installed in the tubes, they provided a reasonably reliable heat balance.

2. Bubble Elimination

When a heated solution is near the boiling point, both air bubbles and vapor bubbles might be generated in the fluid. These bubbles caused the system to become unstable. A vent line was installed at the heater exit which vented any generated bubbles to the atmosphere before the liquid entered the evaporator-condenser.

F. Evaluation of Heat Loss

A special experiment was run with the purpose of determining the heat loss. By using the same apparatus without membrane and a copper sheet, so that there was only one channel, hot water was circulated through the channel for about two hours until the temperature in the channel reached a steady state. The pump was stopped and the temperature of the channel was measured every ten minutes. The drop of temperature was due to heat loss to the air. Then a heat transfer coefficient could be calculated based on the total area exposed and the temperature difference of the inner channel and the outside temperature. The calculation was as follows,

$$Vp\ Cp\ \Delta T = F(A1 + A2 + A3)(T_W - T_A) \cdot t$$

$$F = [Vp\ Cp\ (\Delta T)]/[(A1 + A2 + A3)(T_W - T_A)_m t]$$

V = volume of the channel

p = density of water at the temperature in the channel

ΔT = temperature change with time, °F

Cp = heat capacity of water

A1 = A3, A2 = the areas exposed to the air and refers to channels 1, 2, 3, -ft^2

F = heat transfer coefficient of heat loss

T_W = the mean temperature of the channel water

T_A = the mean temperature of the air (room temperature)

t = time, hr

Three successive different measurements gave results as follows for heat loss coefficient F, BTU/(hr)(ft^2)(°F) .

1. F = 0.7930

2. F = 0.8269

3. F = 0.8172

The average F in 0.8124.

This value was used to estimate heat losses from each channel in the experimental runs.

G. Data and Results

All the data obtained during this investigation were tabulated in the following pages. The following nomenclatures were used in the tables.

G1 = flow rate in hot and cold salt water channels, lb/(hr)(ft^2)

G2 = flow rate of fresh water channel, lb/(hr)(ft^2)

TH = thickness of the membrane, inch

R = gram of Teflon contained per gram of glass fiber membrane

TSI, TSO = hot salt water temperature in inlet and outlet tubes, respectively, °F

TRI, TRO = cold salt water temperatures in inlet and outlet tubes respectively, °F

TSM = bulk mean temperature of hot salt water in the channel, °F

TFM = bulk mean temperature of fresh water in the channel, °F

TRM = bulk mean temperature of cold salt water in the channel, °F

DPM = logrithemic mean vapor pressure difference, (in-Hg)

UM = overall heat transfer coefficient for the membrane.

UC = overall heat transfer coefficient for the copper sheet, BTU/(hr)(ft^2)(°F)

U3 = overall heat transfer coefficient for the membrane by conduction, BTU/(hr)(ft^2)(°F)

DW = mass transfer rate, lb/hr

KM = overall mass transfer coefficient, lb/(hr)(ft^2)(in-Hg)

DATA AND RESULTS

TABLE 1. Temperature, Heat and Mass Transfer Coefficients for the System with Fresh Water and Salt Water Flow.

RUN 1 BOTH FRESH AND SALT WATER FLOWING

G1	G2	TH	R
4186.781000	3488.985000	0.019500	0.522105

TSI	TSO	TRI	TRO	TSM	TFM	TRM	DPM	UM	UC	U3	DW	KM
159.6	147.4	115.5	118.5	148.5	123.0	116.5	3.22	62.15	70.57	14.02	1.08	0.334
159.9	147.5	115.6	118.9	148.8	123.6	116.8	3.21	63.94	74.67	15.15	1.08	0.336
160.4	147.6	115.6	119.2	149.0	124.1	117.1	3.20	66.26	77.45	17.74	1.06	0.332
160.5	147.8	115.6	119.4	149.1	124.5	117.3	3.16	67.26	80.16	19.70	1.03	0.324
162.3	148.3	115.5	119.7	149.2	124.8	117.5	3.16	74.08	83.57	25.02	1.05	0.333
162.9	148.9	115.6	120.2	149.8	125.1	117.7	3.22	73.40	89.82	25.02	1.05	0.325
AVERAGE VALUE												
160.9	147.9	115.6	119.3	149.1	124.2	117.1	3.19	67.35	79.37	19.44	1.06	0.331

TABLE 2.

RUN 2 BOTH FRESH AND SALT WATER FLOWING

G1	G2	TH	R
3324.053000	2770.044000	0.019500	0.522105

TSI	TSO	TRI	TRO	TSM	TFM	TKM	DPM	UM	UC	U3	DW	KM
166.3	149.8	111.3	117.9	151.9	125.6	115.6	3.53	65.31	74.31	16.55	1.12	0.316
166.2	149.5	111.1	117.8	151.8	125.1	115.2	3.57	65.39	74.48	16.99	1.13	0.315
165.5	148.9	110.9	117.4	151.1	124.5	114.6	3.52	64.97	74.58	17.15	1.11	0.316
165.2	148.7	111.2	117.7	150.6	124.2	114.8	3.48	64.67	77.80	16.39	1.12	0.322
165.0	148.4	111.1	117.6	150.4	124.2	115.0	3.43	65.58	78.20	17.46	1.10	0.322
164.3	147.9	111.0	117.4	149.9	124.1	114.9	3.35	66.41	78.13	18.63	1.08	0.322
AVERAGE VALUE												
165.4	148.9	111.1	117.6	150.9	124.6	115.0	3.48	65.37	76.25	17.20	1.11	0.319

TABLE 3.

RUN 3 BOTH FRESH AND SALT WATER FLOWING

G1	G2	TH	R
2435.947000	2029.956000	0.019500	0.522105

TSI	TSO	TRI	TRO	TSM	TFM	TRM	DPM	UM	UC	U3	DW	KM
172.6	150.0	107.6	117.6	151.6	124.5	113.0	3.61	63.34	71.88	12.78	1.20	0.331
172.7	150.6	110.5	118.9	152.2	125.1	114.9	3.66	62.06	70.93	13.96	1.14	0.311
173.9	151.5	114.7	121.4	153.4	126.6	117.5	3.73	62.53	66.06	13.04	1.16	0.311
174.8	152.3	116.4	123.0	155.5	127.7	119.2	4.00	60.19	69.29	13.13	1.14	0.284
174.3	152.3	116.8	123.5	156.5	128.4	120.0	4.11	59.80	70.51	15.41	1.08	0.263
173.9	152.3	117.3	123.9	155.5	128.7	120.6	3.88	62.59	72.31	15.54	1.09	0.282
AVERAGE VALUE												
173.7	151.5	113.9	121.4	154.1	126.8	117.5	3.83	61.75	70.17	13.98	1.13	0.297

TABLE 4.

RUN 4 BOTH FRESH AND SALT WATER FLOWING

G1	G2	TH	R
1674.713000	1395.594000	0.019500	0.522105

TSI	TSO	TRI	TRO	TSM	TFM	TRM	DPM	UM	UC	U3	DW	KM
178.1	149.9	108.0	119.5	149.5	125.0	115.9	3.17	60.06	69.85	15.17	0.96	0.303
176.1	148.7	107.3	118.0	148.5	124.1	114.1	3.08	58.17	62.55	14.05	0.94	0.304
174.9	147.6	108.9	118.3	147.7	123.5	114.3	3.01	59.31	58.08	15.97	0.91	0.303
173.9	147.2	110.1	118.6	146.8	123.2	114.6	2.89	59.06	59.97	14.14	0.92	0.320
174.0	147.1	110.6	119.0	146.5	122.9	115.2	2.88	58.83	64.02	15.52	0.89	0.310
174.0	146.5	110.7	118.8	146.7	122.7	115.3	2.94	58.92	64.49	15.68	0.91	0.309
AVERAGE VALUE												
175.1	147.8	109.3	118.7	147.6	123.6	114.9	2.99	59.06	63.16	15.09	0.92	0.308

TABLE 5.

RUN 5 BOTH FRESH AND SALT WATER FLOWING

G1	G2	TH	R
4186.781000	3489.985000	0.018000	0.656587

TSI	TSO	TRI	TRO	TSM	TFM	TRM	DPM	UM	UC	U3	DW	KM
154.1	142.0	105.3	111.6	143.6	118.0	108.0	2.92	62.23	82.46	20.96	0.94	0.320
151.4	140.0	104.0	109.8	141.5	116.0	106.5	2.78	58.87	81.78	17.95	0.93	0.333
149.3	138.4	102.9	108.3	139.6	114.5	105.4	2.62	57.10	80.39	17.21	0.89	0.338
147.9	137.0	102.2	107.4	138.2	113.5	104.7	2.51	57.10	81.19	17.02	0.88	0.350
146.9	136.1	101.7	106.5	137.1	112.6	104.1	2.44	57.24	76.25	18.87	0.84	0.343
146.1	135.1	101.3	105.9	135.9	111.7	103.5	2.34	59.01	76.47	21.70	0.80	0.342

AVERAGE VALUE

TSI	TSO	TRI	TRO	TSM	TFM	TRM	DPM	UM	UC	U3	DW	KM
149.3	138.1	102.9	108.3	139.3	114.4	105.3	2.60	58.59	79.76	18.95	0.88	0.338

TABLE 6.

RUN 6 BOTH FRESH AND SALT WATER FLOWING

G1	G2	TH	R
5328.632000	4440.527000	0.018000	0.656587

TSI	TSO	TRI	TRO	TSM	TFM	TRM	DPM	UM	UC	U3	DW	KM
143.4	134.6	104.7	107.4	134.7	112.3	105.9	2.14	63.06	76.42	22.87	0.80	0.374
143.5	134.8	104.5	107.6	135.1	112.4	106.0	2.17	60.90	87.52	22.03	0.78	0.359
144.0	135.1	104.8	108.0	135.5	112.9	106.3	2.19	63.73	87.46	24.16	0.79	0.362
144.4	135.3	105.2	108.4	135.9	113.4	106.6	2.20	65.05	86.30	25.13	0.80	0.362
144.6	135.3	105.5	108.7	136.2	113.7	107.0	2.22	67.06	86.45	27.24	0.79	0.358
144.6	135.5	105.8	108.9	136.4	113.9	107.2	2.23	64.77	84.01	24.39	0.81	0.361
AVERAGE VALUE												
144.1	135.1	105.1	108.2	135.6	113.1	106.5	2.19	64.10	84.69	24.30	0.79	0.363

TABLE 7.

RUN 7 BOTH FRESH AND SALT WATER FLOWING

G1	G2	TH	R
1065.726000	888.105700	0.019500	0.522105

TSI	TSO	TRI	TRO	TSM	TFM	TRM	DPM	UM	UC	U3	DW	KM
175.0	143.0	106.0	115.4	135.2	118.0	112.4	1.70	62.62	67.20	18.47	0.67	0.394
173.4	141.7	106.1	114.6	133.2	117.1	112.2	1.53	63.72	65.78	21.09	0.61	0.396
171.9	140.8	105.6	113.8	132.2	116.4	111.2	1.46	64.44	60.59	21.17	0.60	0.411
177.2	142.0	105.1	113.3	132.8	116.4	110.7	1.55	67.96	57.06	23.27	0.65	0.420
180.2	142.6	105.6	113.4	134.0	116.9	111.3	1.63	71.94	58.40	28.57	0.65	0.398
176.0	141.5	106.2	113.8	133.7	116.8	111.5	1.61	66.14	56.86	23.41	0.64	0.395
AVERAGE VALUE												
175.6	142.0	105.8	114.0	133.5	116.9	111.6	1.58	66.14	60.98	22.66	0.64	0.402

TABLE 8.

RUN 8 BOTH FRESH AND SALT WATER FLOWING

G1	G2	TH	R
2435.947000	2029.956000	0.619500	0.522105

TSI	TSO	TRI	TRO	TSM	TFM	TRM	DPM	UM	UC	U3	DW	KM
175.8	160.9	127.7	135.8	159.9	144.1	132.2	2.60	70.30	56.82	21.26	0.55	0.254
175.3	160.2	125.7	134.4	158.9	143.9	131.1	2.43	74.29	58.74	20.20	0.70	0.286
174.4	159.6	125.9	134.5	158.4	144.0	131.5	2.32	76.24	59.56	17.52	0.73	0.314
176.2	160.9	125.5	134.9	159.2	144.4	131.5	2.42	73.71	61.41	15.78	0.74	0.304
177.5	162.2	125.9	135.4	160.9	145.1	131.8	2.63	71.65	61.90	13.74	0.77	0.294
176.7	161.4	126.2	135.5	161.6	145.4	132.2	2.69	70.74	59.84	18.79	0.70	0.261
AVERAGE VALUE												
176.0	160.9	126.2	135.1	159.8	144.5	131.7	2.52	72.82	59.71	17.88	0.72	0.286

TABLE 9.

RUN 9 BOTH FRESH AND SALT WATER FLOWING

G1	G2	TH	R
2435.947000	2029.956000	0.019500	0.522105

TSI	TSO	TFI	TRO	TSM	TFM	TRM	DPM	UM	UC	U3	DW	KM
184.2	164.6	112.9	131.7	167.1	142.9	125.6	4.40	60.69	86.41	9.48	1.04	0.236
184.2	164.9	112.6	131.5	167.6	142.9	125.4	4.53	63.01	84.97	12.96	1.04	0.229
182.0	163.0	113.5	130.8	166.7	142.6	125.2	4.35	59.92	78.82	8.43	1.04	0.239
181.3	163.5	114.0	130.4	166.6	142.9	125.4	4.24	59.88	75.57	7.49	1.03	0.244
182.1	164.4	113.6	130.3	164.9	142.6	125.2	3.90	62.70	76.11	5.55	1.06	0.273
182.9	163.7	113.0	129.9	164.3	142.4	124.7	3.80	68.33	75.88	12.36	1.03	0.271
AVERAGE VALUE												
182.8	164.0	113.3	130.8	166.2	142.7	125.2	4.20	62.42	79.63	9.38	1.04	0.249

TABLE 10. Temperature, Heat and Mass Transfer Coefficients for the System with Salt Water Flow but No Fresh Water Flow.

RUN 1 SALT WATER FLOWING AND NO FRESH WATER FLOW

G1	G2	TH	R
2435.947000	0.000000	0.018000	0.412632

TSI	TSO	TRI	TRO	TSM	TFM	TRM	DPM	UM	UC	U3	DW	KM
156.8	138.7	102.5	112.6	142.5	127.1	114.0	1.81	85.53	64.07	25.36	0.82	0.451
159.0	140.3	103.4	114.4	144.1	129.5	116.4	1.77	93.36	71.00	29.26	0.82	0.463
159.8	141.0	104.1	115.6	145.5	131.0	118.1	1.83	94.16	73.47	27.87	0.85	0.465
160.1	141.9	105.0	116.5	146.9	132.0	119.2	1.93	88.75	75.35	22.92	0.86	0.447
160.9	143.3	105.3	117.1	149.0	133.0	120.4	2.16	78.98	76.94	16.89	0.88	0.405
161.6	144.0	105.6	117.5	149.6	133.6	120.9	2.19	81.49	77.52	19.53	0.87	0.399
AVERAGE VALUE												
159.7	141.5	104.3	115.6	146.3	131.0	118.2	1.95	87.05	73.06	23.64	0.85	0.438

TABLE 11.

RUN 2 SALT WATER FLOWING AND NO FRESH WATER FLOW

G1	G2	TH	R
1065.726000	0.000000	0.020000	0.512500

TSI	TSO	TRI	TRO	TSM	TFM	TRM	DPM	UM	UC	U3	DW	KM
171.6	135.1	104.2	115.9	142.2	128.3	116.2	1.56	80.18	42.57	31.80	0.57	0.365
175.2	138.8	104.9	119.8	147.3	133.2	120.5	1.78	82.26	47.01	24.33	0.70	0.391
177.1	141.1	105.6	122.4	149.3	136.2	123.4	1.71	87.86	51.22	37.67	0.56	0.325
176.3	142.7	106.8	124.7	150.5	138.3	126.1	1.66	87.50	56.46	28.80	0.61	0.371
176.9	143.9	108.4	126.3	150.9	139.5	127.5	1.59	90.79	56.55	29.17	0.61	0.386
175.6	143.5	108.2	125.7	149.4	139.1	126.8	1.36	100.89	52.19	45.40	0.49	0.362
AVERAGE VALUE												
175.4	140.9	106.4	122.5	148.3	135.8	123.4	1.61	88.25	51.00	32.86	0.59	0.367

TABLE 12.

RUN 3 SALT WATER FLOWING AND NO FRESH WATER FLOW

G1	G2	TH	R
1674.713000	0.000000	0.020000	0.512500

TSI	TSO	TRI	TRO	TSM	TFM	TRM	DPM	UM	UC	U3	DW	KM
184.3	156.6	121.4	133.1	162.7	148.6	135.0	2.50	95.62	55.50	27.29	0.83	0.333
185.3	159.5	124.0	136.3	166.0	152.1	138.2	2.66	91.34	55.32	23.51	0.82	0.309
184.6	160.1	125.1	137.9	165.4	154.1	139.9	2.13	109.90	55.79	27.71	0.81	0.382
184.9	160.8	125.2	138.6	166.4	155.6	141.4	2.07	105.49	57.80	21.04	0.80	0.386
186.9	162.5	125.7	139.7	168.7	157.1	143.0	2.34	102.80	61.69	26.10	0.78	0.333
185.7	162.0	125.9	139.8	168.1	157.3	143.9	2.12	108.80	62.57	34.10	0.70	0.331

AVERAGE VALUE

TSI	TSO	TRI	TRO	TSM	TFM	TRM	DPM	UM	UC	U3	DW	KM
185.3	160.3	124.5	137.6	166.2	154.1	140.2	2.30	102.33	58.11	26.62	0.79	0.346

TABLE 13.

RUN 4 SALT WATER FLOWING AND NO FRESH WATER FLOW

G1	G2	TH	R
2435.947000	0.000000	0.020000	0.512500

TSI	TSO	TPI	TPO	TSM	TPM	TRM	DRM	UM	UC	UB	DW	KM
186.7	170.1	139.4	147.3	175.7	164.3	148.3	2.59	102.87	45.69	35.84	0.66	0.256
187.9	171.0	140.5	148.8	176.2	165.3	149.2	2.47	108.89	47.06	33.38	0.71	0.287
188.0	171.7	140.9	149.6	177.3	165.7	149.3	2.70	99.68	47.36	37.30	0.62	0.228
188.4	171.8	141.0	149.3	177.9	165.9	149.4	2.89	96.41	46.96	31.83	0.58	0.235
189.1	171.4	140.9	149.1	177.1	165.4	149.3	2.70	110.29	46.16	48.93	0.62	0.228
185.6	170.4	140.3	148.4	174.5	164.6	149.2	2.38	111.58	48.81	41.31	0.59	0.282
AVERAGE VALUE												
187.6	171.1	140.5	148.5	176.4	165.2	149.1	2.57	104.85	47.01	38.10	0.64	0.252

TABLE 14.

RUN 5 SALT WATER FLOWING AND NO FRESH WATER FLOW

G1	G2	TH	R
3324.053000	0.000000	0.020000	0.512500

TSI	TSO	TRI	TRO	TSM	TFM	TRM	DPM	UM	UC	U3	DW	KM
186.7	175.9	149.9	154.9	179.2	167.9	153.8	2.73	88.90	48.49	26.94	0.61	0.222
188.4	177.5	151.4	156.3	178.8	169.4	155.4	1.78	128.55	45.99	37.92	0.65	0.364
189.4	178.4	151.2	156.5	179.6	171.0	155.8	1.73	122.28	45.27	42.91	0.54	0.312
189.2	178.5	151.2	156.8	181.9	171.1	156.2	2.77	90.32	48.26	28.21	0.59	0.211
189.1	178.4	151.3	156.7	182.2	170.9	156.3	2.92	87.83	47.26	28.24	0.59	0.201
188.3	177.9	151.1	156.4	182.0	170.6	156.2	2.93	85.36	47.64	27.77	0.57	0.195
AVERAGE VALUE												
188.5	177.8	151.0	156.2	180.6	170.1	155.6	2.48	100.54	47.15	32.00	0.59	0.251

TABLE 15.

RUN 6 SALT WATER FLOWING AND NO FRESH WATER FLOW

G1	G2	TH	P
4212.156000	0.000000	0.020000	0.512500

TSI	TSO	TRI	TRO	TSM	TFM	TRM	DPM	UM	UC	U3	DW	KM
189.8	179.9	156.9	160.5	181.9	172.0	159.1	2.53	119.03	48.98	55.97	0.55	0.216
189.3	179.6	157.0	160.5	181.3	172.0	159.1	2.31	124.82	46.35	60.47	0.52	0.226
188.3	179.9	157.0	160.2	181.7	172.3	159.2	2.36	101.84	44.16	34.42	0.55	0.234
188.2	180.6	157.3	160.6	182.4	172.7	159.5	2.50	90.08	44.78	26.81	0.54	0.216
187.1	179.9	157.0	160.4	181.8	172.2	159.7	2.46	84.69	48.13	22.86	0.52	0.213
187.9	179.5	156.7	160.0	181.9	171.9	159.7	2.56	96.87	47.53	33.92	0.55	0.216
AVERAGE VALUE												
188.4	179.9	157.0	160.4	181.8	172.2	159.4	2.45	102.89	46.65	39.08	0.54	0.220

TABLE 16.

RUN 7 SALT WATER FLOWING AND NO FRESH WATER FLOW

G1	G2	TH	R
1065.726000	0.000000	0.019000	0.487500

TSI	TSO	TRI	TRO	TSM	TFM	TRM	DPM	UM	UC	U3	DW	KM
181.6	149.0	93.3	120.6	144.6	128.9	114.1	1.94	57.21	63.59	11.89	0.77	0.395
176.7	147.9	92.9	118.2	142.6	127.6	112.1	1.79	63.31	55.97	7.70	0.74	0.414
179.3	150.3	92.6	116.3	138.2	125.2	109.8	1.40	76.78	52.76	15.06	0.71	0.506
184.1	151.7	93.4	116.2	135.9	124.1	109.4	1.22	87.29	56.36	13.71	0.77	0.635
186.0	152.7	94.5	118.4	137.2	125.4	110.5	1.25	90.32	57.25	18.17	0.75	0.606
186.3	153.6	94.9	119.3	138.2	125.9	110.8	1.32	85.24	56.65	19.45	0.71	0.540
AVERAGE VALUE												
182.3	150.9	93.6	118.1	139.5	126.2	111.1	1.49	78.36	57.10	14.33	0.74	0.516

TABLE 17.

RUN 8 SALT WATER FLOWING AND NO FRESH WATER FLOW

G1	G2	TH	R
1065.726000	0.000000	0.019000	0.487500

TSI	TSO	TRI	TRO	TSM	TFM	TRM	DPM	UM	UC	U3	DW	KM
184.5	153.8	105.4	124.0	140.0	129.1	116.2	1.21	85.59	56.45	18.13	0.65	0.534
185.0	154.4	108.4	126.9	142.2	131.6	118.9	1.23	90.87	55.30	23.88	0.62	0.506
185.7	155.3	109.5	128.3	143.2	133.2	120.3	1.19	94.86	53.94	26.98	0.60	0.504
186.0	156.3	110.0	128.7	143.9	134.1	121.0	1.18	95.00	54.15	24.43	0.61	0.517
186.1	156.5	110.6	129.0	144.7	134.9	122.1	1.21	92.87	54.54	24.66	0.59	0.491
186.4	157.0	111.1	128.9	145.3	135.2	123.0	1.25	92.67	55.28	24.63	0.60	0.483

AVERAGE VALUE

185.6	155.5	109.2	127.6	143.2	133.0	120.3	1.21	91.98	54.94	23.78	0.61	0.506

TABLE 18.

RUN 9 SALT WATER FLOWING AND NO FRESH WATER FLOW

G1	G2	TH	R
1674.713000	0.000000	0.019000	0.487500

TSI	TSO	TRI	TRO	TSM	TFM	TRM	DPM	UM	UC	U3	DW	KM
187.8	164.8	125.7	138.8	157.5	145.4	131.6	1.97	92.76	57.32	28.33	0.69	0.349
186.0	165.6	127.1	139.8	158.3	147.2	134.2	1.83	92.34	56.90	26.29	0.65	0.354
185.8	164.8	125.1	138.5	157.3	146.2	133.0	1.80	91.91	58.57	26.10	0.65	0.359
187.4	165.1	123.9	138.0	157.9	145.9	132.3	1.97	90.15	61.06	25.02	0.69	0.350
188.1	166.1	123.3	137.9	157.8	145.7	131.8	1.99	90.69	60.30	28.44	0.66	0.335
188.4	166.0	123.3	138.0	158.0	146.1	131.8	1.96	90.20	61.92	17.68	0.76	0.389

AVERAGE VALUE

TSI	TSO	TRI	TRO	TSM	TFM	TRM	DPM	UM	UC	U3	DW	KM
187.3	165.4	124.7	138.5	157.8	146.1	132.5	1.92	91.34	59.35	25.31	0.68	0.356

Table 19.

3. Data Used for Least Squares with Equation is Tabulated as Follows:

$$\text{Let } p_p = \frac{2p^2 \times 1.414}{\bar{T}^{0.75}(2p+p_{AS}+p_{AF})po}$$

$$h_h = \frac{1}{f(G.T)_S} + \frac{1}{f(G.T)_F}$$

$\frac{1}{k_m} - \frac{b}{k_D} p_p$	$\frac{(\Delta p)_{Lm}H}{(\Delta T)_{Lm}} h_h$	$p_p\ h_h$	$\frac{b[(\Delta T)_{Lm}-Z]}{\bar{T}}$
1.64	16.59	3.78	
1.67	16.96	3.76	
1.78	18.57	4.05	
1.76	17.13	3.75	
1.85	19.13	4.00	
1.76	18.62	4.04	
1.76	18.44	4.05	
1.66	16.83	3.77	
1.64	16.72	3.78	
1.73	17.13	3.75	

The following data were used for least squares with equation 4-6

1.64	16.59	3.78	0.65
1.73	17.13	3.75	0.62
1.66	16.83	3.77	0.63
1.83	19.13	4.00	0.66
1.76	18.44	4.05	0.65
1.76	18.62	4.04	0.67

H. Computer Programs

The computer programs were used for the computations described in this thesis and are given in this appendix. The programs were written in Fortran IV language and were run in an IBM 360 system.

```
/WAT4  CN120288,TIME=1,PAGES=10  D          LEE,J.M.                     JOB
C CNCS490F LEE,JING-MING RESEARCH ANALYSIS CACULATION
C HEAT AND MASS TRANSFER ANALYSIS PROGRAM
C WSI FLOW PER HOUR LB/HR.
C TMC,HTC,HTRC ARE THE MASS AND HEAT TRANSFER COEFFICIENT.
C TSIFM,TSOFM,TFIFM,TFOFM,TRIFM,TROFM ARE THE MEAN TEMP.DURING PERIOD
C DW IS THE COLLECTED WATER AMOUNT
C DPM,DTM ARE THE LOG MEAN VALUE OF PRESS AND TEMP. RESPECT TO S.AND F. WATER
C V1 IS THE SALTY WATER CHAMBER VOLUME TIMES DENSITY
C V2 IS THE FRESH WATER CHAMBER VOLUME TIMES DENSITY
      DIMENSIONTSIF(10),TSOF(10),TFIF(10),TFOF(10),TRIF(10),TROF(10)
      DIMENSION  TS(10),TF(10),TR(10)
      DIMENSION TF1(10),TF2(10),TF3(10),TF4(10)
      DIMENSION TFR(10)
      AR=1.5*16.25/12.**2
      V1=(16.5*1.5*0.5/12**3)*61.3
      V2=(16.5*1.5*0.6/12**3)*61.3
      J=9
      DO 10 I=1,J
   44 F=0.81243
  222 READ(1,101) W,THICK,WT,TWT
  101 FORMAT(6F10.5)
   88 AQC=0.
      APS=0.
      APF=0.
      AH=0.
      AT=0.
      AKM=0.
      AUM=0.
      AUC=0.
      AU=0.
      ADW=0.
      ADTM=0.
      ADPM=0.
      TT1=0.
      TT2=0.
      TT3=0.
      TT4=0.
      TF5=0.
      TF6=0.
      TF7=0.
      WRITE(3,100) I
      WRITE(3,105)
      WSI=W*60./454.
   55 WFI=0.
      TFW=(TWT-WT)/WT
      THICK=THICK/1000.
      CA1=1.5*0.5/12.**2
```

Continued on next page.

```
      CA2=1.5*0.6/12.**2
      SF=WSI/CA1
      FF=WFI/CA2
      G1=SF
      G2=FF
      VVF=WFI/(CA2*62.4*3600.)
      VVS=WSI/(CA1*62.4*3600.)
      WRITE(3,400) SF,FF,THICK,TFW
      WRITE(3,150)
  400 FORMAT(/3X,4(3X,F12.6))
  100 FORMAT(1H1,/////4X,'RUN',I4,2X,'FOR FRESH WATER NO FLOW')
  105 FORMAT(///12X,'G1',12X,'G2',15X,'TH',12X,'R')
  150 FORMAT(/2X,'TSI',3X,'TSO',3X,'TRI',3X,'TRO',3X,'TSM',3X,'TFM',3X,
     1'TRM',3X,'DPM',5X,'UM',4X,'UC',4X,'U3',4X,'DW',4X,'KM')
      DO 20 K=1,7
      READ(1,102)ESI,ESO,EFI,EFO,ERI,ERO,TCR
      READ(1,102) ET1,ET2,ET3,ET4
      ESI=ESI+TCR/24.49
      IF(ESI-2.45)1,1,2
    1 TSI =ESI*24.49
      GO TO 3
    2 TSI = 60.0+(ESI-2.45)*21.74
    3 ESO=ESO+TCR/24.49
      IF ( ESO-2.45)4,4,5
    4 TSO = ESO*24.49
      GO TO 6
    5  TSO=60.0+(ESO-2.45)*21.74
    6 EFI=EFI+TCR/24.49
      IF(EFI-2.45)7,7,8
    7  TFI= EFI*24.49
      GO TO  9
    8  TFI=60.0+(EFI-2.45)*21.74
    9 EFO = EFO+TCR/24.49
      IF(EFO-2.45)11,11,12
   11  TFO = EFO*24.49
       GO TO 13
   12  TFO=60.0+(EFO-2.45)*21.74
   13 ERI= ERI+TCR/24.49
      IF(ERI-2.45)14,14,15
   14 TRI= ERI*24.49
      GO TO  16
   15 TRI= 60.0+ (ERI-2.45)*21.74
   16 ERO =ERO +TCR/24.49
      IF (ERO-2.45) 17,17,18
   17 TRO =ERO*24.49
      GO TO 21
   18 TRO=60.0+(ERO-2.45)*21.74
   21 ET1=ET1+TCR/24.49
```

Continued on next page.

```
      IF(ET1-2.45)22,22,23
   22 T1=ET1*24.49
      GO TO 24
   23 T1=60.+(ET1-2.45)*21.74
   24 ET2=ET2+TCR/24.49
      IF(ET2-2.45)25,25,26
   25 T2=ET2*24.49
      GO TO 27
   26 T2=60.+(ET2-2.45)*21.74
   27 ET3=ET3+TCR/24.49
      IF(ET3-2.45)28,28,29
   28 T3=ET3*24.49
      GO TO 31
   29 T3=60.+(ET3-2.45)*21.74
   31 ET4=ET4+TCR/24.49
      IF(ET4-2.45) 32,32,33
   32 T4=ET4*24.49
      GO TO 34
   33 T4=60.+(ET4-2.45)*21.74
   34 TSIF(K)=(TSI-2.*(TSI-TCR)/(100.-TCR))*1.8+32.0
      TSOF(K)=(TSO-2.*(TSO-TCR)/(100.-TCR))*1.8+32.0
      TFIF(K)=(TFI-2.*(TFI-TCR)/(100.-TCR))*1.8+32.0
      TFOF(K)=(TFO-2.*(TFO-TCR)/(100.-TCR))*1.8+32.0
      TRIF(K)=(TRI-2.*(TRI-TCR)/(100.-TCR))*1.8+32.0
      TROF(K)=(TRO-2.*(TRO-TCR)/(100.-TCR))*1.8+32.
      TF1(K)=(T1-2.*(T1-TCR)/(100.-TCR))*1.8+32.
      TF2(K)=(T2-2.*(T2-TCR)/(100.-TCR))*1.8+32.
      TF3(K)=(T3-2.*(T3-TCR)/(100.-TCR))*1.8+32.
      TF4(K)=(T4-2.*(T4-TCR)/(100.-TCR))*1.8+32.
      TS(K)=(TSIF(K)+TSOF(K))/2.
      TF(K)=(TFIF(K)+TFOF(K))/2.
      TR(K)=(TRIF(K)+TROF(K))/2.
      TFR(K)=TCR*1.8+32.
   20 CONTINUE
      DO 30 N=1,6
      A=3.2438
      B=5.8683E-3
      C=1.1702E-8
      D=2.1878E-3
      READ(1,102)TIME,DW
      TSI=((TSIF(N)+TSIF(N+1))/2.-32.)/1.8
      TSO=((TSOF(N)+TSOF(N+1))/2.-32)/1.8
      TFI=((TFIF(N)+TFIF(N+1))/2.-32.)/1.8
      TFO=((TFOF(N)+TFOF(N+1))/2.-32.)/1.8
      TRI=((TRIF(N)+TRIF(N+1))/2.-32.)/1.8
      X1=374.11-TSI
      S1=2.303*X1/(TSI+273.16)*(A+B*X1+C*X1**3)/(1.+D*X1)
      X2=374.11-TSO
```

Continued on next page.

```
      S2=2.303*X2/(TSO+273.16)*(A+B*X2+C*X2**3)/(1.+D*X2)
      Y1=374.11-TFI
      F1=2.303*Y1/(TFI+273.16)*(A+B*Y1+C*Y1**3)/(1.+D*Y1)
      Y2=374.11-TFO
      F2=2.303*Y2/(TFO+273.16)*(A+B*Y2+C*Y2**3)/(1.+D*Y2)
      PS1=6528.5*EXP(-S1)
      PS2=6528.5*EXP(-S2)
      PF1=6528.5*EXP(-F1)
      PF2=6528.5*EXP(-F2)
      PS1=PS1*0.96
      PS2=PS2*0.96
      DP1=PS1-PF2
      DP2=PS2-PF1
      DPM=(DP1-DP2)/(ALOG(DP1)-ALOG(DP2))
      DW=DW*60./(TIME*454.)
      DW1=DW/AR
      TMC=DW1/DPM
      TSIFM=(TSIF(N)+TSIF(N+1))/2.
      TSOFM=(TSOF(N)+TSOF(N+1))/2.
      TFIFM=(TFIF(N)+TFIF(N+1))/2.
      TFOFM=(TFOF(N)+TFOF(N+1))/2.
      TRIFM=(TRIF(N)+TRIF(N+1))/2.
      TROFM=(TROF(N)+TROF(N+1))/2.
      TFM1=(TF1(N+1)+TF1(N))/2.
      TFM2=(TF2(N+1)+TF2(N))/2.
      TFM3=(TF3(N+1)+TF3(N))/2.
      TFM4=(TF4(N+1)+TF4(N))/2.
      DT1=TSIFM-TFOFM
      DT2=TSOFM-TFIFM
      DTM=(DT1-DT2)/(ALOG(DT1)-ALOG(DT2))
      TSM=(TSIFM+TSOFM)/2.
      TFM=(TFIFM+TFOFM)/2.
      TRM=(TRIFM+TROFM)/2.
      H1=1126.1+0.396*(TSM-150)
      H2=TFM-32.
      DH=H1-H2
      DH1=DW*H1
      QCD=DW*DH
      QT=(TFM1-32.0)*WSI-(TFM2-32.0 )*(WSI-DW)-V1*(TS(N+1)-TS(N))
     1*60./TIME
      QR=(TFM3-TFM4)*WSI+V1*(TR(N+1)-TR(N))*60./TIME
      QACF=V2*(TF(N+1)-TF(N))*60./TIME+DW*(TFOFM-32.)
      TCR=(TFR(N+1)+TFR(N))/2.
      A1=((21.*0.75)*2.+16.5*1.5)/144.
      A2=(21.*0.6)*2./144.
      A3=A1
```

Continued on next page.

```
      QL1=A1*F*(TSM-TCR)
      QL2=A2*F*(TFM-TCR)
      QL3=A3*F*(TRM-TCR)
      QC1=QT-QL1
      QC2=QR+QL3
      QC=QT-DH1-QL1
      DT=TFM-TRM
      AU1=QC1/(DTM*AR)
      AU2=QC2/(DT*AR)
      AU3=QC/(DTM*AR)
      WRITE(3,201)TFM1,TFM2,TFM4,TFM3,TSM,TFM,TRM,DPM,AU1,AU2,AU3,
     1 DW1,TMC
      PS=(PS1+PS2)/2.
      PF=(PF1+PF2)/2.
      APS=APS+PS
      APF=APF+PF
      AH=AH+DH
      TT1=TT1+TFM1
      TT2=TT2+TFM2
      TT3=TT3+TFM3
      TT4=TT4+TFM4
      TF5=TF5+TSM
      TF6=TF6+TFM
      TF7=TF7+TRM
      ADW=ADW+DW1
      AKM=AKM+TMC
      ADTM=ADTM+DTM
      ADPM=ADPM+DPM
      AUM=AUM+AU1
      AUC=AUC+AU2
      AU=AU+AU3
      AQC=AQC+QC
   30 CONTINUE
      WRITE(3,111)
      TFM1=TT1/6.
      TFM2=TT2/6.
      TFM3=TT3/6.
      TFM4=TT4/6.
      TSM=TF5/6.
      TFM=TF6/6.
      TRM=TF7/6.
      DPM=ADPM/6.
      TMC=AKM/6.
      DW1=ADW/6.
      AU1=AUM/6.
      AU2=AUC/6.
      AU3=AU/6.
      DTM=ADTM/6.
```

Continued on next page.

```
      PS=APS/6.
      PF=APF/6.
      WRITE(3,201)TFM1,TFM2,TFM4,TFM3,TSM,TFM,TRM,DPM,AU1,AU2,AU3,
     1DW1,TMC
   10 CONTINUE
  111 FORMAT(//3X,' AVERAGE VALUE' )
  201 FORMAT(/7F6.1,F6.2,F7.2,3F6.2,F6.3)
  102 FORMAT(7 F10.5)
      STOP
      END
```

/DATA

```
      C     GENERAL PROGRAM TO TEST THE NULL HYPOTHESIS
      C     LINEAR REGRESSION
      C     MODEL IS : Y(I)=B(0)+SUM OF B(J)*X(J)          J=1,2,3,.....,IP
      C     NP=NO. OF PARAMETERS=IP+1
      C     REWRITE THE MODEL AS FOLLOWING:
      C        Y=X0*B(0)+X1*A1+X2*A2
      C        WHERE A1 IS A (IQ*1) VECTOR
      C              A2 IS A ((IP-IQ)*1) VECTOR
      C     TESTING H0 : A2=0
            DIMENSION B(25),X(50,20),XC(1000),Y(50),XT(20,50),XTC(1000)
            DIMENSION XTX(20,45),XTXC(400),XTY(20),AI(20,20),CPID(20)
            DIMENSION CR(20,45),R(20,45),S(20,20),T(50,20),YH(50),DY(50)
            READ(1,500)MP
            DO 499 MMP=1,MP
            WRITE(3,505)MMP
            READ(1,500)N,IP,IQ
            NP=IP+1
      C     READ IN BY ROW
            DO 1 I=1,N
          1 READ(1,510) Y(I),(X(I,J),J=1,NP)
            DO 455 MM=1,2
            IF(MM-1)7,7,2
          2 IPQ=IP-IQ
            DO 6 I=1,N
            DO 3 K=1,IPQ
            K1=K+1
            K2=K1+IQ
          3 T(I,K1)=X(I,K2)
            DO 4 KK=1,IQ
            KK1=KK+1
            KK2=KK1+IPQ
          4 T(I,KK2)=X(I,KK1)
            DO 5 J=2,NP
          5 X(I,J)=T(I,J)
          6 CONTINUE
            WRITE(3,701)
            GO TO 9
          7 WRITE(3,700)
          9 DO 8 I=1,N
          8 WRITE(3,710)(X(I,J),J=1,NP)
      C     TRANSFORM X TO SINGLE SUBSCRIPT VECTOR
            DO 10 K=1,NP
            DO 10 J=1,N
            I=J+(K-1)*N
         10 XC(I)=X(J,K)
      C     TRANSPOSE X MATRIX : XT (NP BY N)
```

Continued on next page.

```
      CALL GMTRA(XC,XTC,N,NP)
      DO 15 I=1,NP
      DO 15 J=1,N
      K=I+(J-1)*NP
   15 XT(I,J)=XTC(K)
C     PRODUCT OF XT*X : XTX (NP BY NP)
      CALL GMPRD(XTC,XC,XTXC,NP,N,NP)
      DO 20 I=1,NP
      DO 20 J=1,NP
      K=I+(J-1)*NP
   20 XTX(I,J)=XTXC(K)
C     PRODUCT OF XT*Y : XTY (NP BY 1)
      CALL GMPRD(XTC,Y,XTY,NP,N,1)
C     IDENTITY MATRIX : AI (NP BY NP)
      DO 40 I=1,NP
      DO 35 J=1,NP
      IF(I-J)25,30,25
   25 AI(I,J)=0.
      GO TO 35
   30 AI(I,J)=1.
   35 CONTINUE
   40 CONTINUE
C     AUGMENT XTX MATRIX TO INCLUDE XTY AND AI
      NP1=NP+1
      NN=NP+1+NP
      DO 50 I=1,NP
      XTX(I,NP1)=XTY(I)
      DO 45 J=1,NP
      JJ=NP1+J
   45 XTX(I,JJ)=AI(I,J)
   50 CONTINUE
C     PROCEDE DOOLITTLE METHOD
      DO 55 J=1,NN
      CR(1,J)=XTX(1,J)
   55 R(1,J)=CR(1,J)/CR(1,1)
      DO 68 I=2,NP
      DO 65 J=I,NN
      IM1=I-1
      SUM=0.
      DO 60 K=1,IM1
   60 SUM=SUM+R(K,I)*CR(K,J)
      CR(I,J)=XTX(I,J)-SUM
   65 R(I,J)=CR(I,J)/CR(I,I)
   68 CONTINUE
      IF(IP-4)69,69,72
   69 WRITE(3,720)
      DO 70 I=1,NP
```

Continued on next page.

```
   70 WRITE(3,730)(XTX(I,J),J=1,NN)
      DO 76 I=1,NP
      L=I-1
      GO TO (71,72,73,74,75),I
   71 WRITE(3,740)L,(CR(I,J),J=I,NN)
      WRITE(3,750)L,(R(I,J),J=I,NN)
      GO TO 76
   72 WRITE(3,741)L,(CR(I,J),J=I,NN)
      WRITE(3,751)L,(R(I,J),J=I,NN)
      GO TO 76
   73 WRITE(3,742)L,(CR(I,J),J=I,NN)
      WRITE(3,752)L,(R(I,J),J=I,NN)
      GO TO 76
   74 WRITE(3,743)L,(CR(I,J),J=I,NN)
      WRITE(3,753)L,(R(I,J),J=I,NN)
      GO TO 76
   75 WRITE(3,744)L,(CR(I,J),J=I,NN)
      WRITE(3,754)L,(R(I,J),J=I,NN)
   76 CONTINUE
C     BACK SUBSTITUTION TO OBTAIN B VECTOR
      B(NP1)=0.
      DO 80 I=1,NP
      L=NP1-I
      SUM=0.
      DO 78 J=1,I
      LL=L+J
   78 SUM=SUM+R(L,LL)*B(LL)
   80 B(L)=R(L,NP1)-SUM
C     CALCULATE INVERSE OF XTX : S (NP BY NP)
      DO 95 I=1,NP
      II=NP1+I
      DO 90 J=I,NP
      JJ=NP1+J
      SUM=0.
      DO 85 K=1,NP
   85 SUM=SUM+R(K,II)*CR(K,JJ)
   90 S(I,J)=SUM
   95 CONTINUE
      DO 96 I=2,NP
      IM1=I-1
      DO 96 J=1,IM1
   96 S(I,J)=S(J,I)
      WRITE(3,760)
      DO 97 I=1,NP
   97 WRITE(3,731)(S(I,J),J=1,NP)
C     CALCULATE CROSS PRODUCT IN DOOLITTLE : CPID
      WRITE(3,521)
      DO 100 I=1,NP
```

Continued on next page.

```
      III=I-1
      CPID(I)=CR(I,NP1)*R(I,NP1)
  100 WRITE(3,531)III,CPID(I)
      WRITE(3,520)
      DO 101 I=1,NP
      III=I-1
  101 WRITE(3,530)III,B(I)
      IF(MM-1)102,102,105
  102 WRITE(3,770)
      DO 104 I=1,N
      SUM=0.
      DO 103 J=1,NP
  103 SUM=SUM+B(J)*X(I,J)
      YH(I)=SUM
      DY(I)=Y(I)-YH(I)
  104 WRITE(3,780)Y(I),YH(I),DY(I)
C     SST=TOTAL(UNCORRECTED) SSQ
C     SSRG=REGRESSION SSQ
C     SSRS=RESIDUAL SSQ
  105 S1=0.
      DO 106 I=1,N
  106 S1=S1+Y(I)*Y(I)
      SST=S1
      S2=0.
      DO 107 I=1,NP
  107 S2=S2+CPID(I)
      SSRG=S2
      SSRS=SST-SSRG
      SSO=CPID(1)
      SSRO=SSRG-SSO
      NQ2=IQ+2
      SUM=0.
      DO 110 I=NQ2,NP
  110 SUM=SUM+CPID(I)
      SSPQ=SUM
      NR=N-NP
      ASSRO=SSRO/IP
      NPQ=IP-IQ
      ASSRS=SSRS/NR
      F1=ASSRO/ASSRS
      WRITE(3,540)
      WRITE(3,550)N,SST
      WRITE(3,560)SSO
      WRITE(3,570)NP,SSRG
      WRITE(3,580)IP,SSRO,ASSRO,F1
      IF(MM-1)115,115,120
```

Continued on next page.

```
  115 ASSPQ=SSPQ/NPQ
      F2=ASSPQ/ASSRS
      WRITE(3,590)NPQ,SSPQ,ASSPQ,F2
      GO TO 125
  120 ASSPQ=SSPQ/IQ
      F2=ASSPQ/ASSRS
      WRITE(3,591)IQ,SSPQ,ASSPQ,F2
  125 WRITE(3,610)NR,SSRS,ASSRS
C     MULTIPLE CORRELATION COEFFICIENT
      R2=SSRO/(SST-SSO)
      WRITE(3,620)R2
      WRITE(3,660)IP,NR
      IF(MM-1)130,130,135
  130 WRITE(3,660)NPQ,NR
      GO TO 140
  135 WRITE(3,660)IQ,NR
  140 WRITE(3,661)NR
  455 CONTINUE
  499 CONTINUE
  500 FORMAT(7I10)
  505 FORMAT(1H1,//,2X,'PROBLEM ',I1)
  510 FORMAT(7F10.4)
  520 FORMAT(///,2X,'PARAMETERS ARE')
  521 FORMAT(///,2X,'CROSS PRODUCT IN DOOLITTLE ARE')
  530 FORMAT(/,5X,'B(',I2,')=',E13.5)
  531 FORMAT(/,5X,'CPID(',I2,')=',F12.4)
  540 FORMAT(//,8X,'SOURCE',9X,'DF',9X,'SS',17X,'MS',15X,'CAL F')
  550 FORMAT(//,2X,'TOTAL(UNCORRECTED)',2X,I3,2X,F12.4)
  560 FORMAT(//,2X,'R(BO)',17X,'1',2X,F12.4)
  570 FORMAT(//,2X,'REGRESSION(B)',7X,I3,2X,F12.4)
  580 FORMAT(//,2X,'R(B:BO)',13X,I3,2X,F12.4,5X,'MSR=',F12.4,F15.4)
  590 FORMAT(//,2X,'R(A2:B(O),A1)',7X,I3,2X,F12.4,4X,'MS12=',F12.4,
     1F15.4)
  591 FORMAT(//,2X,'R(A1:B(O),A2)',7X,I3,2X,F12.4,4X,'MS21=',F12.4,
     1F15.4)
  610 FORMAT(//,2X,'RESIDUAL',12X,I3,2X,F12.4,4X,'S**2=',F12.4)
  620 FORMAT(///,2X,'MULTIPLE CORRELATION COEFFICIENT IS',//,8X,'R**2=',
     1F7.4)
  660 FORMAT(//,2X,'TABULATED F(',I2,',',I2,')=')
  661 FORMAT(//,2X,'TABULATED F( 1,',I2,')=')
  700 FORMAT(//,1X,'MODEL : Y=XO*B(O)+X1*A1+X2*A2',//,2X,'X MATRIX IS')
  701 FORMAT(//,1X,'MODEL : Y=XO*B(O)+X2*A2+X1*A1',//,2X,'X MATRIX IS')
  710 FORMAT(/,8X,11F10.2)
  720 FORMAT(//,2X,'DOOLITTLE PRINT OUT')
  730 FORMAT(/,8X,11F10.2)
  731 FORMAT(/,8X,10F11.4)
  740 FORMAT(/,2X,'CR(',I1,')',11F10.2)
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Continued on next page.

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  741 FORMAT(/,3X,'CR(',I1,')',10X,10F10.2)
  742 FORMAT(/,3X,'CR(',I1,')',20X,9F10.2)
  743 FORMAT(/,3X,'CR(',I1,')',30X,8F10.2)
  744 FORMAT(/,3X,'CR(',I1,')',40X,7F10.2)
  750 FORMAT(/,4X,'R(',I1,')',11F10.2)
  751 FORMAT(/,4X,'R(',I1,')',10X,10F10.2)
  752 FORMAT(/,4X,'R(',I1,')',20X,9F10.2)
  753 FORMAT(/,4X,'R(',I1,')',30X,8F10.2)
  754 FORMAT(/,4X,'R(',I1,')',40X,7F10.2)
  760 FORMAT(//,2X,'INVERSE OF XTX IS')
  770 FORMAT(///,11X,'Y',10X,'YH',9X,'DY')
  780 FORMAT(/,5X,3F10.2)
      STOP
      END
```

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IX. VITA

Jing Ming Lee was born on December 25, 1934, in Pao-Shan, Kiangsu, China. He entered the Department of Chemical Engineering, Chung-Yuan College of Science and Engineering (Taiwan Christian College) in September 1957 and graduated in June 1961 with a Bachelor of Science Degree in Chemical Engineering.

From 1963 to 1967 he worked in an Ammonia-Urea plant, Mobil China Allied Chemical Industries Ltd., Miaoli, Taiwan, China.

He enrolled in the University of Missouri at Rolla in September 1967 as a graduate student in the Chemical Engineering Department.