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CONTINUOUS COUNTERCURRENT EVAPORATION THROUGH POROUS WATER-REPELLENT MEMBRANE WITH PRESSURE ABOVE ATMOSPHERIC

BY

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A

THESIS

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ABSTRACT

An experimental method for measuring mass transfer rates at pressures above atmospheric has been developed for the case of continuous countercurrent evaporation through porous water-repellent membranes. The final developed equipment is suitable for operation under pressures up to 50 psig and at temperatures near the boiling point of 7% salt water when high flow rates are reached.

Rates of evaporation of water through the membrane were measured, and the data and results were used to examine the effects of operating conditions on the over-all mass transfer resistance. Least-squares equations for fitting the data were also obtained.

Over-all mass transfer coefficients were found to be a strong function of pressures and to depend slightly on flow rates and the log-mean partial pressure of the stagnant air in the membrane.

The experimental method should be useful for the study of evaporation through porous membranes for application to commercial sea water conversion.

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NOMENCLATURE

A = surface area of membrane, sq. ft.

a_s = fraction of the area of solids in membrane

a_v = fraction of the area of vapor space in membrane

b = thickness of membrane, ft.

b_1 = average equivalent thickness of solid part of membrane, ft.

b_2 = average equivalent thickness of pores of membrane, ft.

C = concentration of water, lb./cu.ft.

C' = concentration of vapor in membrane, lb./cu.ft.

D_{AB} = binary diffusivity, sq.ft./hr.

D_e = effective diffusivity, sq.ft./hr.

G = mass flow rate of salt water, lb./hr.sq.ft.

H = Henry's law constant

h = film heat transfer coefficient, Btu/hr.sq.ft.°F

H_v = enthalpy of water vapor in membrane, Btu/lb.

k = thermal conductivity, Btu/lb. ft.°F

K_m = over-all mass transfer coefficient, lb./hr.sq.ft. in. Hg

k_G = individual mass transfer coefficient in terms of partial pressures, lb./hr.sq.ft. in.Hg

k_L = individual mass transfer coefficient in terms of concentrations, lb./hr.sq.ft. (lb./cu.ft.)

k_1 = average conductivity of the solid of membrane, Btu/hr.ft.°F

k_2 = average conductivity of the air-vapor mixture in membrane, Btu/hr.ft.°F

N_A = rate of diffusion of water vapor, lb./hr.sq.ft.

P = total pressure, in.Hg

p = partial pressure, in.Hg

p_{BM} = log-mean partial pressure of air, in.Hg

Δp_m = log-mean partial pressure drop of water vapor, in.Hg

Q = heat transfer rate, Btu/hr.

q = heat transfer rate per unit area, Btu/hr.sq.ft.

q_c = heat transfer rate per unit area by conduction, Btu/hr.sq.ft.

q_1 = heat flux per unit area through the solid of the membrane, Btu/hr.sq.ft.

q_2 = heat flux per unit area through the pores of the membrane, Btu/hr.sq.ft.

R = gas-law constant

R_M = mass transfer resistance in the membrane in terms of partial pressures, in.Hg/(lb./hr.sq.ft.)

r_M = heat transfer resistance in the membrane, °F/(Btu/hr.sq.ft.)

T = absolute temperature, °R

t = temperature, °F

$\bar{T}$ = average absolute temperature in the membrane, °R

Δt_m = log-mean temperature drop, °F

U = over-all heat transfer coefficient, Btu/hr.sq.ft.°F

V = mass transfer rate of water vapor, lb./hr.

W = mass flow rate of liquid, lb./hr.

x = mass fraction

z = distance in the direction of diffusion, ft.

Subscripts:

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

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

s, f, referring to salt water and fresh water, respectively.

I. INTRODUCTION

Vaporization through porous membranes has become a possible method for desalting sea water as suggested by Findley (8). Briefly it involves removing water from aqueous solution by vaporization through a porous, water-repellent membrane, and condensation into a coolant on the other side. The geometric requirements for the process are met by a porous membrane containing vapor with a solution layer on one side and a condensate layer on the other side. A single pore, with liquids excluded, acts as a small single stage of flash evaporation. On this basis a porous membrane could act as an infinite stage evaporation system.

For design applications, one important phase of study concerning this method is the prediction of performance under various conditions, especially those under continuous operation. Previous studies (14, 15, 20, 23) provided some information about the relation between heat and mass transfer and evaluated the effects of membrane character and operating conditions on the transfer properties. However an investigation on the effects of high pressure and temperature conditions is needed in order to establish the possibility of the commercial application of this method.

The purposes of this investigation were to develop a bench-scale continuous flow evaporator and perform a few experimental runs for prediction of the effects of pressure and flow rate on mass and heat transfer.

II. LITERATURE REVIEW AND THEORIES

In this investigation a water-repellent membrane was used. A hot salt solution was placed in contact with one side of the membrane and sufficiently cooler fresh water was placed in contact with the other side. These liquids were held out of the membrane by surface tension forces. When the vapor pressure at the hot salt solution surface was greater than the vapor pressure at the cooler liquid surface, vaporization would occur at the solution surface and the hot vapor would move through the pores of the membrane by diffusion through the stagnant air in the pores to the cooler surface where they would condense. Latent heat was transfered as in conventional evaporation, and also sensible heat was transfered through the membrane by conduction.

At present there are few satisfactory theories or models available for use in predicting diffusion of gases in porous media. A transfer process consists of a net flow of a quantity under the influence of a driving force. The driving force for this transfer process is the temperature for heat transfer and the corresponding vapor pressure gradient for mass transfer between the surfaces of the membrane.

A. Rate Equations:

The rate equations for mass and heat transfer are presented below:

1. The Transfer of Mass: Transfer through the membrane is by diffusion, it is fundamentally no different from liquid system diffusion (22), and in theory the same law applies.

(1) Fick's Law of Diffusion: This law is applied to the movement of one species, say A, through a binary mixture of A and B driven by the concentration gradient of A. Mathematically it is expressed as (2):

$$N_A = x_A(N_A + N_B) - cD_{AB}\nabla x_A \qquad (2\text{-}1)$$

where N_A, N_B = molar flux of A and B, respectively

x_A = molar fraction of A

c = total molar concentration

D_{AB} = binary diffusivity

∇ = "gradient" operator

(2) Steady-state Diffusion of One Gas through a Second Stagnant Gas: Here, $N_B = 0$, and if gas A diffuses in z direction from z_1 to z_2, from Eq. (2-1) the following equation can be derived (3,18):

$$N_A = \frac{D_{AB}P}{RT(z_1-z_2)} \frac{p_{A1}-p_{A2}}{p_{BM}} \qquad (2\text{-}2)$$

where P = total pressure

T = constant absolute temperature

R = gas constant

p_{A1}, p_{A2} = partial pressures of A at z_1 and z_2, respectively

$$p_{BM} = \frac{p_{B2}-p_{B1}}{\ln(p_{B2}/p_{B1})} \tag{2-3}$$

p_{B2} and p_{B1} are the partial pressures of the gas B at z_2 and z_1, respectively.

This states that the rate of diffusion is directly proportional to the decrease in partial pressure of the diffusing gas A and inversely proportional to the length of the path and to the logarithmic mean of the extreme values of the partial pressures of the interfering inert gas B.

(3) Steady-State, Equal-Molal Counter Diffusion of Two Gases: Here, $N_A = -N_B$, Eq. (2-1), after integration, becomes:

$$N_A = \frac{D_{AB}(p_{A1}-p_{A2})}{RTz} \tag{2-4}$$

which differs from Eq. (2-2) for one diffusing gas only by substitution of P for p_{BM}. In the case of gas A diffusing through stagnant gas B, as long as the partial pressures of the diffusing gas at z_1 and z_2 are small when compared with the total pressure (i. e., x_A in Eq. (2-1) is very much smaller than 1). Eq. (2-4) can be used instead of Eq. (2-2)(7).

2. The Transfer of Heat: In a case of a hot fluid that is separated from a cold fluid by a solid wall, conduction of heat is taking place in the interior of the solid body while convection and conduction of heat is taking place from its surface.

(1) Fourier's Equation of Heat Conduction: For the transfer of heat by conduction, Fourier's law is valid:

$$q = \frac{k}{b} (t_1 - t_2) \qquad (2\text{-}5)$$

where q is the heat flux per unit area, b is the thickness of the wall or the film thickness from the wall, $(t_1 - t_2)$ is the temperature difference and k is the thermal conductivity.

(2) Newton's Law of Cooling: If the fluid motion in the region immediately adjacent to the surface of the wall is laminar, the heat flux in this region may be evaluated in terms of the fluid temperature gradient at the surface:

$$q = h\,(t_1 - t_2) \qquad (2\text{-}6)$$

where h is known as the film coefficient, which depends on the properties of the fluid and on the nature and geometry of the fluid motion past the surface (5).

B. Transport Process between Phases:

As was mentioned before, heat and mass were transferred simultaneously through the porous membrane. Fig. II-1 depicts the concentration and temperature profiles in this transport process, which consists of three phases - hot salt water, membrane, and cold fresh water. The membrane includes solid and pores which are filled with stagnant air and diffusing water vapor. The transports of mass and heat through this process are discussed separately in the following sections:

1. Multiple Phase Resistances: It has already been established that the rate of transfer, be it heat or mass, is equal to the driving

force divided by a resistance. In multiple phase transport process, if the resistances associated with phases are in series, these resistances are additive at steady state (10). In general, then, for steady state

$$\text{Rate} = \frac{\sum_{j=1}^{j=n} (\Delta\Gamma)_j}{\sum_{j=1}^{j=n} R_j} \qquad (2\text{-}7)$$

where $\Delta\Gamma$ is the driving force across the resistance R, and n is the number of phases.

2. Definition of Mass Transfer Coefficient: In Fig. II-1 there are four resistances to the movement of water between three phases, since no appreciable diffusion resistance occurs in the cold fresh water. These resistances are associated with the hot salt water, the interface between the hot salt water and the membrane, the membrane, and the interface between the membrane and the cold fresh water. The interface resistances are assumed to be negligible in most applications (17). The problem is then simplified and will be considered as transfer in the salt water and the membrane only.

In Fig. II-1, C_{A1}', at the surface is in equilibrium with C_{A1}, and C_{A2}' is in equilibrium with C_{A2}. Diffusion from fluid I to the surface of the membrane results from a concentration gradient in the fluid boundary layer, with a concentration drop, $C_{As} - C_{A1}$ across it. The mass transfer coefficient k_L is defined as

$$k_L = \frac{N_A}{C_{As} - C_{A1}} \qquad (2\text{-}8)$$

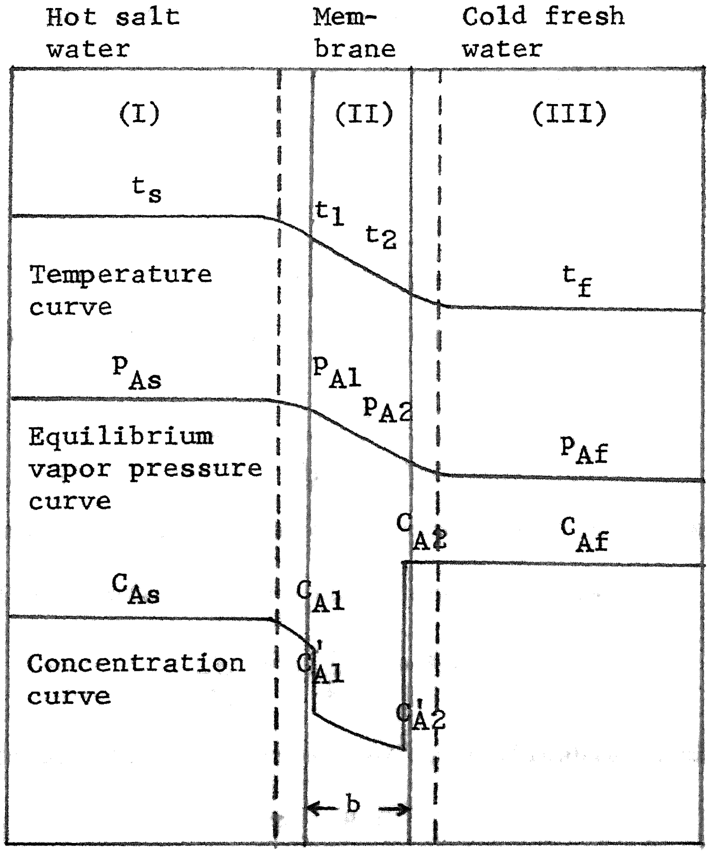


Fig. II-1 Temperature and Concentration Profiles in Simultaneous Mass and Heat Transfer through Porous, Water-Repellent Membranes

t_s = bulk temperature of hot salt water

t_f = bulk temperature of cold fresh water

t_1, t_2 = surface temperatures of membrane

C_{Af} = bulk concentration of fresh water

C_{As} = bulk concentration of salt water

C_{A1}, C_{A2} = concentrations of water vapor at interfaces

C'_{A1}, C'_{A2} = concentrations of water vapor in membrane, at surfaces

p_{As} = equilibrium vapor pressure of water on salt water

PAf = equilibrium vapor pressure of water on fresh water

p_{A1}, p_{A2} = equilibrium vapor pressures of water at interfaces

Taking the partial pressures of water corresponding to C_{As} and C_{A2} to be p_{As} and p_{A2}, one may define an "over-all" mass transfer coefficient by

$$K_m = \frac{N_A}{p_{As} - p_{A2}} \tag{2-9}$$

Eq. (2-8), in terms of partial pressures, becomes

$$k_G = \frac{N_A}{p_{As} - p_{A1}} \tag{2-10}$$

Let R_M represent the resistance of the membrane in terms of partial pressures, and by employing Eq. (2-7) one can show that

$$\frac{1}{K_m} = \frac{1}{k_G} + R_M \tag{2-11}$$

For dilute solution, Henry's law is applicable, and

$$p = H\ C \tag{2-12}$$

whence

$$k_L = H\ k_G \tag{2-13}$$

and

$$\frac{1}{K_m} = \frac{H}{k_L} + R_M \tag{2-14}$$

The over-all mass transfer coefficient defined by Eq. (2-9) is not applicable in this experiment, because p_{A2} corresponds to the vapor pressure of water at the membrane-fresh water interface, which is difficult to determine. For convenience, it is better to define K_m in terms of bulk water conditions which are easily determined. Thus

$$K_m = \frac{N_A}{p_{As} - p_{Af}} \tag{2-15}$$

3. Diffusion in Porous Membranes: Transfer across a porous membrane can sometimes be described as a diffusion process. If the mass flux at the surface is given by Eq. (2-2) which is derived with consideration of the convective flux as well as the diffusive flux through the membrane, an effective diffusivity may be defined (11) as

$$N_A = \frac{D_e P}{RTb} \frac{p_{A1}-p_{A2}}{p_{BM}} \qquad (2\text{-}16)$$

In which, b is the thickness of the membrane, D_e is the effective diffusivity.

4. Definition of Heat Transfer Coefficient: In the case shown in Fig. II-1 we do not know t_1 and t_2, the temperatures of both surfaces of the membrane, but only the temperatures of the liquids on both sides of the membrane. The temperature gradient is confined to a relatively narrow layer quite close to the membrane. This narrow layer depends to a very great extent upon the external flow conditions. In practice we define film heat-transfer coefficients for both liquids by Eq. (2-6), or

$$h_s = \frac{q_c}{t_s - t_1} \qquad (2\text{-}17)$$

$$h_f = \frac{q_c}{t_2 - t_f} \qquad (2\text{-}18)$$

Where q_c is the heat flux per unit area by conduction, and h_s and h_f are film heat-transfer coefficients for salt water and fresh water respectively. If r_M represents the resistance in the membrane and the over-all heat transfer coefficient is defined by

$$U = \frac{q_c}{t_s - t_f} \tag{2-19}$$

then, by using the rule of Eq. (2-7)

$$\frac{1}{U} = \frac{1}{h_s} + r_M + \frac{1}{h_f} \tag{2-20}$$

5. Heat Transfer in Porous Membranes: There is little information available about the heat transfer mechanism with simultaneous mass diffusion through porous membranes (16). However, a model of the heat transfer process might include two parallel processes:

(1) Heat transfer through the solid part of the membrane by conduction.

(2) Heat transfer through the pores of the membrane by conduction and enthalpy transport.

If q_1 and q_2 represent the heat flux per unit area of membrane for the first and second processes respectively, then

$$q_1 = \frac{k_1}{b_1} a_s(t_1 - t_2) \tag{2-21}$$

and

$$q_2 = \frac{k_2}{b_2} a_v(t_1 - t_2) + N_A H_v \tag{2-22}$$

where a_s and a_v are the fractions of the membrane area made up of solid and vapor space, respectively, k_1 and k_2 are the average conductivities of the solid and the mixture of the air and vapors in the pores, and b_1 and b_2 are the average equivalent thicknesses of the solid and the pores, respectively. $N_A H_v$ is an enthalpy stream per unit membrane area and time caused by the water-vapor diffusion. Assuming the temperature drop across the membrane is small, then H_v, the enthalpy of the diffusing vapor, is taken at the average temperature, $(t_1+t_2)/2$. In order to calculate q_1 and q_2, we must have knowledge of the structure of the pores in the membrane and its void fraction from which we might be able to estimate surface areas of the solid and the pores and b_1 and b_2. The simplest physical model assumes all of the pores are in parallel, so, $b_1 = b_2 = b$, and

$$q_1 + q_2 = \frac{1}{b} (k_1 a_s + k_2 a_v)(t_1 - t_2) + N_A H_v \qquad (2\text{-}23)$$

For convenience, we take a combined value of $k_1 a_s$ and $k_2 a_v$ as k_c, then

$$q = \frac{k_c}{b} (t_1 - t_2) + N_A H_v = q_c + N_A H_v \qquad (2\text{-}24)$$

where $q = q_1+q_2$, the total heat flux per unit membrane area, b is the thickness of the membrane and q_c is the total heat flux per unit membrane area by conduction.

In evaluating the experimental results of this study, the overall heat transfer coefficient was estimated by considering the heat conduction only, and Eq. (2-20) was taken as

$$\frac{1}{U} = \frac{1}{h_s} + \frac{b}{k_c} + \frac{1}{h_f} \qquad (2\text{-}25)$$

6. Continuous Countercurrent Process: In experiments on a countercurrent process, when we calculate the over-all mass and heat transfer rates by using Eq. (2-15) and (2-19), it is assumed that log mean Δp

and log mean Δt are appropriate driving forces. Then

$$K_m = \frac{\bar{N}_A}{\Delta p_m} \qquad (2\text{-}26)$$

where

$$\Delta p_m = \frac{\Delta p_1 - p_2}{\ln(\Delta p_1/\Delta p_2)} \qquad (2\text{-}27)$$

Δp_1 and Δp_2 are the differences in water vapor pressures produced by the temperature differences of the two liquids at the two ends of the section under consideration.

$$U = \frac{\bar{q}_c}{\Delta t_m} \qquad (2\text{-}28)$$

where

$$\Delta t_m = \frac{\Delta t_1 - \Delta t_2}{\ln(\Delta t_1/\Delta t_2)} \qquad (2\text{-}29)$$

Δt_1 is the temperature difference between the salt water inlet temperature and fresh water outlet temperature, $t_{is}-t_{of}$, and Δt_2 is the corresponding temperature difference, $t_{os}-t_{if}$, at the salt water outlet and fresh water inlet. In Eq. (2-26) and (2-28) $\bar{N}_A$ and $\bar{q}_c$ are the average mass and conductive heat transfer rates per unit area, respectively.

C. Correlation of Transfer Coefficient:

1. Diffusion in Stationary Fluid and Membrane: Yeh (23) compiled his experimental data on evaporation of salt water through a porous water-repellent membrane. He suggested that these data can be cor-

related successfully by

$$\frac{1}{K_m} = \left(\frac{2}{h}\right) \frac{\Delta p}{\Delta t} \Delta H_v + \left(\frac{4k_e}{k_2 h}\right) \frac{P^2}{(2P + p_s + p_f)\sqrt{\bar{T}}} + \left(\frac{2}{k_2}\right) \frac{P^2 b}{(2P + p_s + p_f)\sqrt{\bar{T}}} \qquad (2\text{-}30)$$

where

h = film heat transfer coefficient, assuming $h_s = h_f = h$, Btu/ft.^{2} hr.°F

Δp = pressure gradient, $(p_s - p_f)$, in. Hg

Δt = temperature drop, $(t_s - t_f)$, °F

ΔH_v = latent heat of vaporization, Btu/lb.

k_e = effective thermal conductivity of membrane, Btu/ft.^{2} hr.(°F/ft.)

k_2 = constant

P = total pressure, in. Hg

p_s = equilibrium partial pressure of water vapor on the salt water side, in. Hg

p_f = equilibrium partial pressure of water vapor on the fresh water side, in. Hg

$\bar{T}$ = average absolute temperature, °R

b = thickness of membrane, ft.

This is a theoretical equation, derived from Eq. (2-1). K_m is defined by Eq. (2-15). This equation is suitable for use in correlating data when independent variables in each term of the equation are taken as parameters and a least-square method is employed.

The terms in parentheses can be assumed constant, and values of the least-squares coefficients provide estimates of these characteristics of the system.

Rao (14) in his thesis pointed out that (Δt - E), where E is the boiling point elevation, has a strong effect on over-all mass transfer resistance, $1/K_m$. He proposed an equation which provided the best fit for his experimental data, as follows:

$$\frac{1}{K_m} = A_1(\Delta t - E)b + A_2 \frac{\Delta p}{\Delta t} \Delta H_v + A_3(\Delta t - E) \qquad (2\text{-}31)$$

where A_1, A_2, and A_3 are constants.

2. Diffusion in Laminar Flow System: Rohatgi (15) in a similar operation as in this investigation found the effects of flow rate of heat and mass transfer coefficients at 1 atm. pressure as shown in the following equations:

$$h_s = K_1(G)^{1.42} \qquad (2\text{-}32)$$

$$K_m = K_2(G)^{.265} \qquad (2\text{-}33)$$

K_1 and K_2 are constants, and G is mass flow rate, in lb./hr.sq.ft. He also observed that K_m increases linearly with $1/p_{BM}$, where p_{BM} is the logarithmic mean of partial pressures of air, and is defined by Eq. (2-3).

3. Transfer Coefficients for High Mass-Transfer Rates: The relation between the mass transfer coefficient and the partial pressure of the diffusing component is generally assumed to follow the theoretical equation for diffusion (Eq. 2-2) if the flow in the direction of

diffusion is appreciable:

$$k_g = \frac{D_{AB}}{RTz} \left(\frac{P}{p_{BM}}\right) \qquad (2\text{-}34)$$

where k_g is the mass transfer coefficient. The function P/p_{BM}, sometimes called the "drift factor" (13), represents the enhancement of transfer due to the total flow in the direction of diffusion. When the partial pressure of the diffusing gas is small compared with the total pressure P, the drift factor approaches unity. According to Eq. (2-34) the mass transfer coefficient k_g should be directly proportional to the drift factor P/p_{BM}.

An investigation of simultaneous transfer of heat and mass between air and water in a wetted-wall column reported by Cairns and Roper (6) has shown that P/p_{BM} has an effect on mass and heat transfer coefficients at high humidities.

A few heat and mass transfer problems for flow between parallel porous plates have been discussed in the literature (1, 21). Also some publications concerning the performance for reverse osmosis in systems under continuous operation through membrane conduits have recently appeared in the literature (19, 9).

III. EXPERIMENTAL

It has been the main purpose of this work to develop bench-scale equipment for the investigation of the mass and heat transfer during water evaporation through an existing type of membrane by continuous countercurrent operation under various conditions, especially for finding the pressure effects on the transport properties through the membrane.

The equipment was first set up for atmospheric pressure operation, and a few trial runs under different flow conditions were made. Then the equipment was changed so that it could be operated satisfactorily under higher pressure.

This final equipment seems to be capable of operation under the following conditions:

Pressure ---- Up to 50 psig
Flow rate ---- Up to 0.2 cu.ft./hr.
Temperature ---- Up to 300 °F
Flow system ---- Continuous countercurrent operation with the same flow rate on both sides of the membrane

A. Development of Apparatus

A rectangular Membrane-Evaporator-Condensor (Refer to Fig. III-1) was employed for this investigation. Flows of fresh and salt water were provided by two Zenith metering pumps at the same speed. Flows could be controlled by the metering controller on a Zero-Max drive power block, maintaining two equal volumetric flows, the hot salt solution and cold fresh water. The power was supplied by a 1/6 horsepower motor.

The energy required for the evaporation was provided by a gas burner, heating the salt solution fluid up to the desired temperature at a position near the entrance. The desired pressure could be built up with compressed air which was introduced through a pressure regulator into the air line system before the circulation was started.

The system maintaining liquid feeds to the apparatus consisted of two liquid reservoirs. Two glass tubes were installed vertically for measuring the volume changes when mass transfer occurred during the operation.

Four thermocouples which were placed at the two entrances and the two exits of the apparatus were used to measure the temperatures with the aid of a potentiometer. A pressure gauge connected to the air pipe above the apparatus was used for measuring the pressure.

The apparatus utilized 1/4" copper tubing and suitable fittings so that a closed liquid circulating and compressed air system was maintained. The liquid circulating part was carefully insulated and the heat loss through the apparatus to the atmosphere was considered negligible.

Mass transfer rates were determined by measuring the time required for particular volume decreases of the salt solution in the glass tube.

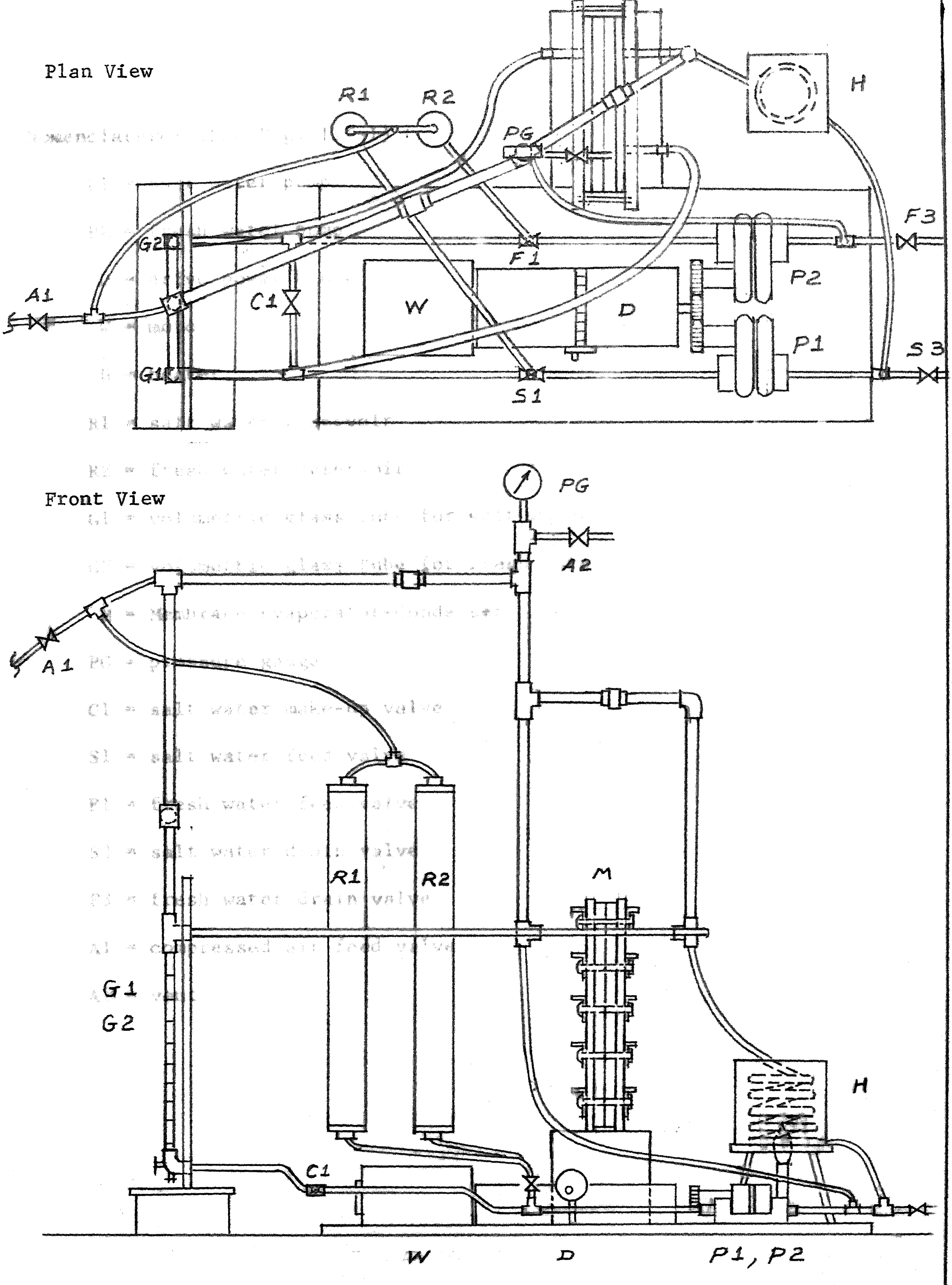


Fig. III-1 Assembly Layout Elevation

Nomenclature: (For Fig. III-1)

P1 = salt water pump
P2 = fresh water pump
D = drive power block
W = motor
H = heater
R1 = salt water reservoir
R2 = fresh water reservoir
G1 = volumetric glass tube for salt water
G2 = volumetric glass tube for fresh water
M = Membrane-Evaporator-Condenser
PG = pressure gauge
C1 = salt water make-up valve
S1 = salt water feed valve
F1 = fresh water feed valve
S3 = salt water drain valve
F3 = fresh water drain valve
A1 = compressed air feed valve
A2 = vent

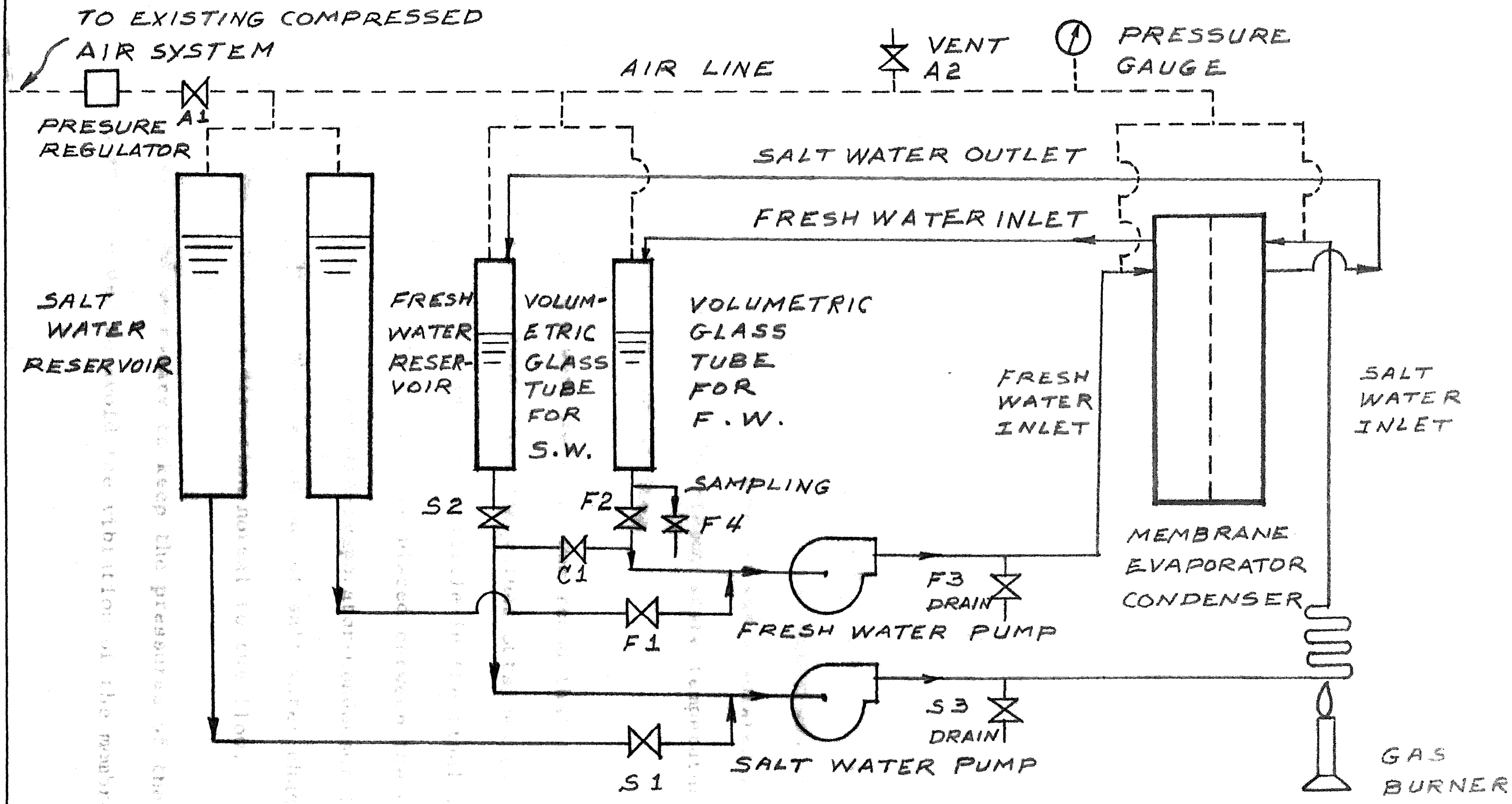


Fig. III-2 Cycle Flow Diagram of Experimental Process

B. Apparatus Trouble and Solutions:

The apparatus which was described in the previous section was the final version used for high pressure experiments. During the development of this apparatus some problems were found and solved. The problems and their solutions are discussed briefly as follows:

Temperature: An inlet temperature near the boiling point of the salt water solution was desired in this investigation. For the atmospheric operation, a water bath heated by an electric heater was able to supply the needed energy. Nevertheless, much more energy was needed when the equipment was changed to operate under higher pressures. A heater consisting of copper tubing and a gas burner was then employed. Also the liquid circulation section was insulated more carefully to reduce the energy loss. The steady state temperature could then be reached in a short period of time.

After a few trial runs were made, it was found that the mass transfer coefficients were lower than the values obtained by other observers (20, 23). This was improved a little in the final experimental run when two pieces of rubber were placed between the channels and the aluminum plates of the Membrane-Evaporator-Condenser to minimize the transfer of heat from inlet to outlet salt water channels through the channel wall in a direction normal to the flow.

Pressure: It was found necessary to keep the pressures of the two channels the same in order to avoid the vibration of the membrane and the leakage of the liquids through the membrane. The two outlet 1/2" tubes were adjusted to run horizontally at the same elevation and a 1/2" pipe above the liquid level was connected to the two inlet 1/4" tubes of the apparatus to equalize the pressures.

Bubble Elimination: At temperatures near the boiling point of the liquid, air bubbles as well as vapor bubbles might be generated in the fluid. If the bubbles were brought into the apparatus, the outlet streams would become unstable, and so would the levels in the volumetric glass tubes. Thus the 1/2" pressure balance pipe was moved from its old location at the outlets of the apparatus to a position near the entrances. The bubbles in the hot solution were then able to escape through the pipe before entering the apparatus.

Air Leakage through Membrane Edges: The membrane that was used in this investigation permitted only the vapor and gas to pass. If the pressure in the membrane became lower than the liquid pressure, the liquids might penetrate into the membrane due to the pressure difference. For high pressure operation, the pressure in the membrane was applied by compressed air which was introduced at the very beginning of the operation. However, the air within the membrane apparently leaked out of the system under operating conditions even when no liquid leaks were apparent, and this allowed liquids to penetrate the membrane. The only way for this air to leak was from the edges of the membrane which were held between gaskets, but were exposed to the outside atmosphere at the edges in the original design. To improve this, one of the gaskets was remade to keep the edges of the membrane from being exposed to the atmosphere (See Fig. III-3).

Liquid Reservoirs: Two burets of 250 milliliters were used as liquid reservoirs in the first design. The liquids in the burets at atmospheric pressure were pumped into the system under higher pressure. It was found that the pumps were not suitable for pumping the liquids against a pressure difference over 30 psi. This problem was then eliminated when the burets were replaced by two new reservoirs made from 1 1/2" pipes with their top ends connecting to the compressed air system. This made the pressure in the reservoirs the same as in the whole system.

Salt Water Level Make-up: While the system was running, the level of the salt water in the volumetric glass tube was drawing down gradually due to the evaporation. After each reading was taken, the salt water level was made up from the fresh water by opening the connecting valve, C1. This make-up step was difficult to achieve sometimes when the air above the liquid levels in the glass tubes was trapped and could not maintain its constant pressure. This problem was solved by a 1/2" pipe connected to the air system at the top of each glass. Thus the air pressure in the tubes could be held constant by the system air.

C. Apparatus:

The apparatus used in this work are listed and described as follows:

Membrane-Evaporator-Condenser (Fig. III-3 to Fig. III-7): This consisted of two aluminum plates and two pairs of rubber gaskets with a porous water-repellent membrane placed between them to separate two narrow rectangular channels for the salt solution fluid and fresh water fluid, respectively. Both of the channels are 3/8" thick, 2" wide and approximately 20" long, with a cross-section area of 0.0052 sq.ft. One of the rubber gaskets on the salt solution side was made different from the others with a thinner inside edge to fit the size of the membrane (Fig. III-3). The whole assembly was tightened with five pairs of steel angle supports.

Liquid Reservoirs: Two liquid reservoirs made of 1 1/2" pipes were used for feeding the liquids to the apparatus. The top ends of the reservoirs were connected to the air line, while their bottom ends were connected to the inlets of the pumps.

Volumetric Glass Tubes: Two 5/8" glass tubes of 15 milliliters each were used as liquid accumulators, from which the volume changes of the liquids could be measured when mass transfer occurred during the operation.

Heater: This consisted of a copper coil and a gas burner. The copper coil was installed inside a square chamber at a position near the entrance of the Membrane-Evaporator-Condenser. The fluid passing through the coil was heated to a desired temperature by the gas burner before it entered the evaporator.

Motor, Drive and Pumps: Two Zenith metering pumps were used for maintaining the circulation of the continuous countercurrent flow. The pumps were driven by a Zero-Max drive power block, model E1, speed range 0-135. The energy was supplied by a Zero-Max motor, model M2, 1/6 horsepower, V115, RPM 725.

Thermocouples: Four thermocouples, Cu-Const., size 20 A.W.G., were used to measure the two entrance and two exit temperatures of the fluids. They were placed near the membrane surface, and the measurements were considered to be bulk temperatures of the fluids.

Potentiometer: A potentiometer was used to measure the e.m.f. of the thermocouples in millivolts. The e.m.f. values were then converted to temperature units to give bulk temperatures of the liquids.

Miscellaneous: Copper tubing, pipe, and fittings were used for connecting the equipment. An electric stirrer, a rectangular filter, and an electric oven (Fig. III-8 and III-9) were used for making the membrane.

D. Materials:

The materials used in this investigation are listed below:

Salt (Sodium Chloride): Reagent grade NaCl was used for preparing 7.0% by weight salt water solution.

Distilled Water: Steam condensate from the condensate line was used.

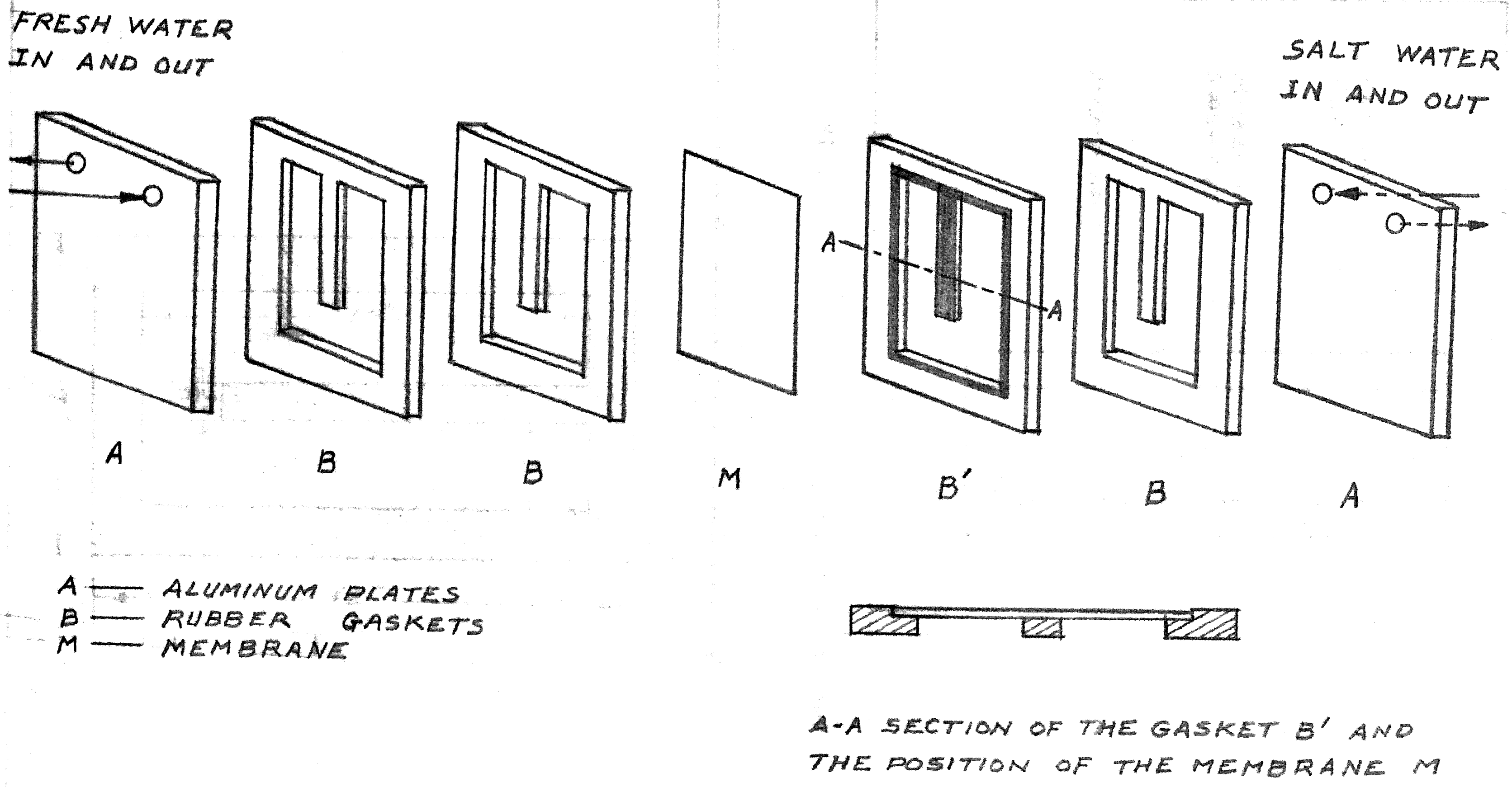


Fig. III-3 Schematic Arrangement of the Membrane-Evaporator-Condenser

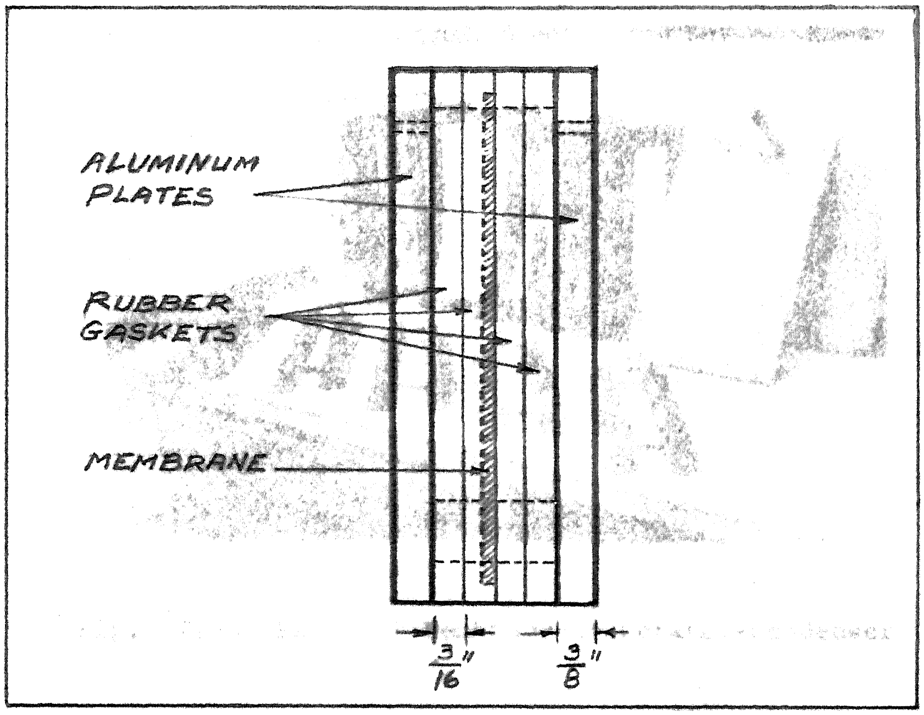


Fig. III-4 Membrane-Evaporator-Condenser

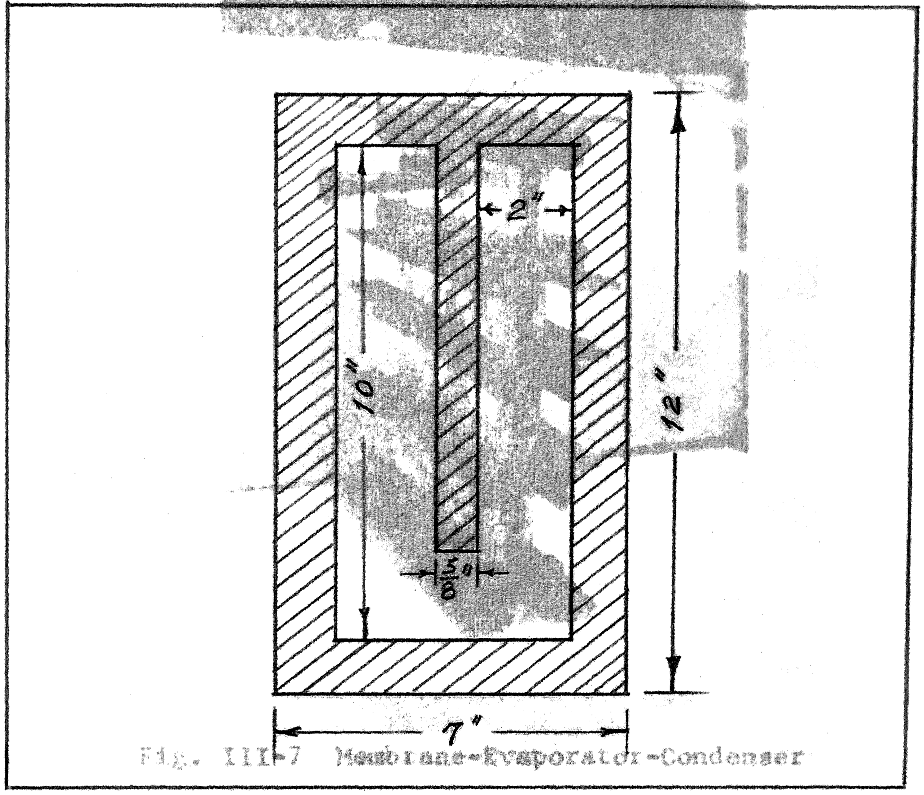


Fig. III-5 Gasket

Fig. III-6 Parts of Membrane-Evaporator-Condenser

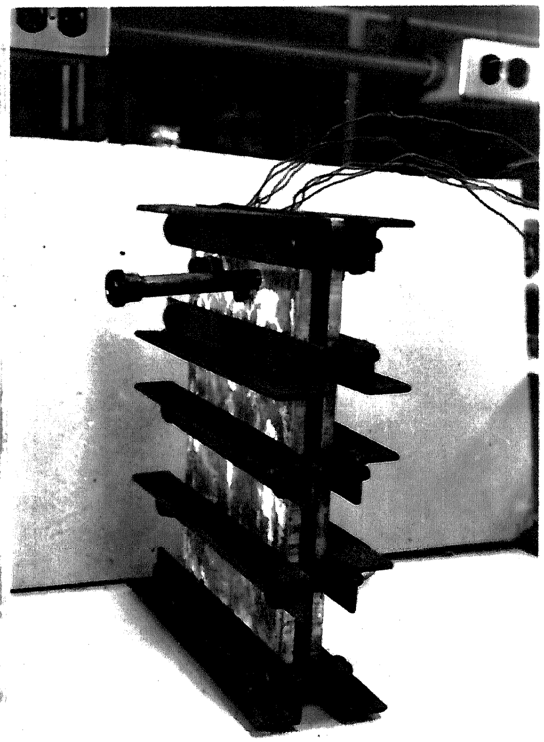


Fig. III-7 Membrane-Evaporator-Condenser

and Its Supports

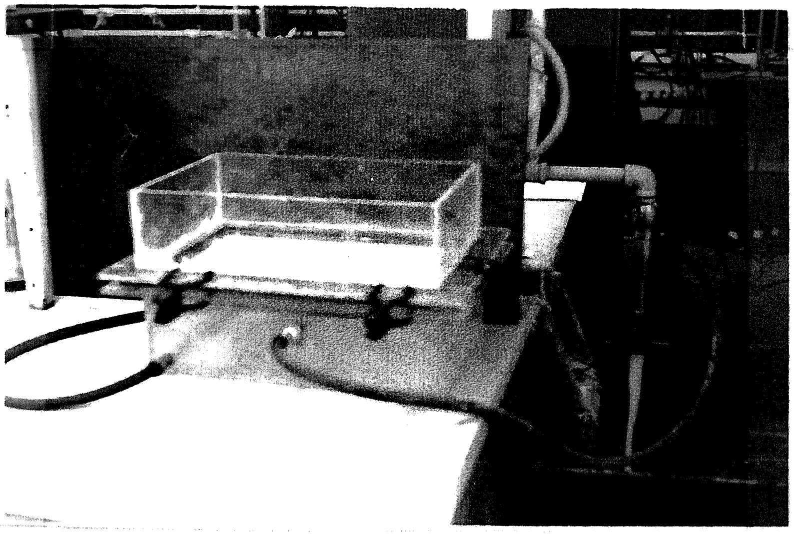


Fig. III-8 Filtration Box (For making membrane)

Fig. III-9 Electric Stirrer and Oven (For making membrane)

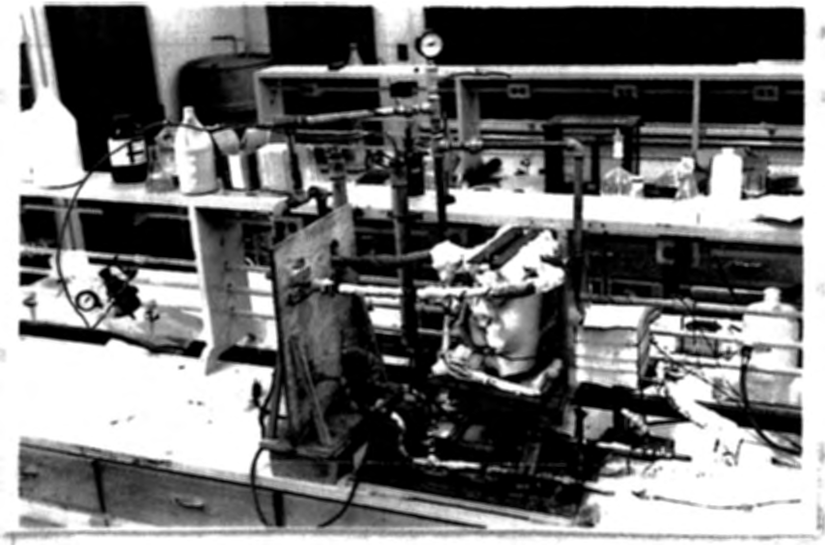


Fig. III-10 Final Developed Equipment

Silver Nitrate: Reagent grade silver nitrate was used to test for Cl^- ions present in the condensate.

Glass Fiber: Owens-Corning "Fiberglas", Type AA, of size 1 micron in diameter was used for making the membranes.

Teflon Dispersion: E. I. Dupont's Teflon 30-B dispersion was used for making the membranes. It is an aqueous dispersion containing 59.0 to 61.0% solids. It has a density of 1.5 $gm./cm.^3$, a PH of 10.0 and a viscosity of 15.0 centipoise at room temperature.

Aluminum Sulfate: Reagent grade aluminum sulfate crystals were used for preparing 0.05 gm./ml. solution.

Acetic Acid: Glacial acetic acid of reagent grade was used.

E. Procedures:

1. Experimental Procedure (Refer to Fig. III-2):

The first step in preparing the system for an experimental run was to fill the salt water and fresh water reservoirs. These liquids were brought separately to two pump charging lines when valves F1 and S1 were opened. Subsequently, the liquids were allowed to fill the glass tubes from the bottom to certain levels to permit the air to escape. The valves F2 and S2 were then closed to prevent the liquids from overflowing.

With the above completed, the compressed air was then introduced gradually to the system to build up a desired pressure which could be adjusted by the pressure regulator, valve A1 or A2. It appeared better to set A1 widely open and A2 slightly open.

The salt water and fresh water pumps were started, and the two liquids were pumped into the apparatus at the same flow rate. As soon as both sides of the apparatus were full and overflow streams were observed into the volumetric glass tubes, valves F2 and S2 were opened. At this time, the fluids were circulating and the two liquid levels in the glass tubes were expected to be stable. Valves F1 and S1 were then closed to isolate the liquid circulation system. Finally, the gas burner was started, and the start-up procedure was completed.

Temperature was increased slowly. The range of temperature differences between the two bulk flows in the channels of the apparatus was desired to be less than 30°F, and sometimes, a second gas burner was needed for maintaining the small temperature difference by heating up the fresh water inlet tube.

Once steady state was reached, the salt water inlet and outlet, fresh water inlet and outlet temperatures and the volumetric mass transfer rates were measured, and the flow rates and the pressures were also measured. Data for calculations were not taken until a steady state was achieved as indicated by constant temperatures.

2. Membrane Preparation:

The membrane studied in this work was made of glass fiber treated with teflon dispersion and aluminum sulphate. The teflon imparts to the membrane the water-repellent character which is the essence of this method of desalination, and the aluminum sulphate improves the retention of teflon. The procedure for making the membrane is described below:

A quantity of 6.6 grams of Owens-Corning fiberglas type AA was weighed and split into small pieces. These pieces were put in a plastic container containing about two liters of distilled water. Then 0.6 ml. acetic acid were added to make the fiber glass disperse easily. The slurry was stirred with an electric stirrer for about ten minutes.

About 3.28 ml. of teflon dispersion was added and mixed with the stirrer for ten minutes. Then approximately 26 ml. of 5% aluminum sulfate solution was added and again stirred for another ten minutes. The slurry formed was allowed to stand for about twenty minutes to give time for the teflon particles to settle on the fibers.

A rectangular box, 8 in. by 12 in., made with Plexiglas and a fine wire screen was used for filtration. Water was fed from the bottom of the box to a level that just touched the screen. The slurry was poured over the screen from the open top of the filtration box, and agitated slightly to obtain a uniform coverage of the fiber glass slurry over the screen. The water was drained by opening an outlet from the bottom to a 1/2" I.D. rubber tube 4 feet long which provided some suction Subsequently, a wet sheet was formed on the surface of the screen. The moisture was partially removed from the wet sheet by pressing with a few paper towels and the sheet was then removed from the screen.

The sheet was placed between several layers of paper towels, and further pressed by a heavy roller with several changes of paper towels until it was difficult to remove additional water in this manner. The membrane was then heated in an oven at 550 °F for thirty minutes.

The membranes had a density of 0.162 gm./cm.^{3}, a porosity of 0.9 and a thickness of 0.0745 cm.

F. Calculation Procedure:

The experimental data were used to calculate

1. The over-all mass transfer coefficient, K_m
2. The over-all heat transfer coefficient, U

Fig. III-11 shows heat and mass balances in a countercurrent system which was used in this investigation. Assume

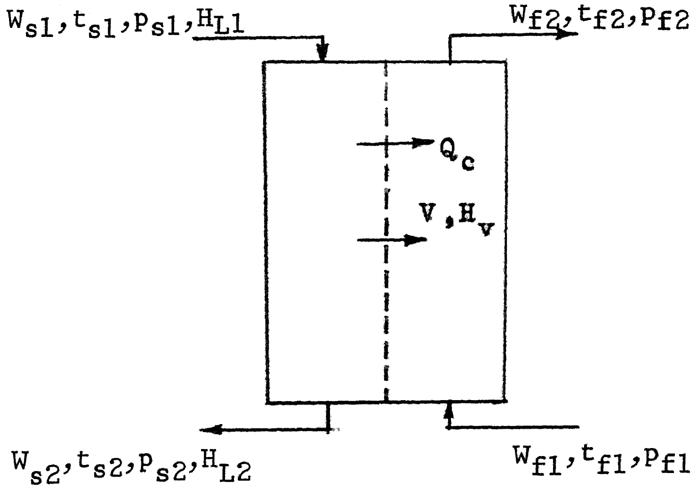


Fig. III-11 Countercurrent Evaporation through Porous Membrane

W_{s1} = mass flow rate of salt water in, lb./hr.

W_{s2} = mass flow rate of salt water out, lb./hr.

W_{f1} = mass flow rate of fresh water in, lb./hr.

W_{f2} = mass flow rate of fresh water out, lb./hr.

t_{s1} = salt water inlet temperature, °F

t_{s2} = salt water outlet temperature, °F

t_{f1} = fresh water inlet temperature, °F

t_{f2} = fresh water outlet temperature, °F

p_{s1} = vapor pressure of water at salt water inlet, in. Hg

p_{s2} = vapor pressure of water at salt water outlet, in. Hg

p_{f1} = vapor pressure of water at fresh water inlet, in. Hg

p_{f2} = vapor pressure of water at fresh water outlet, in. Hg

H_{L1} = enthalpy of salt water at t_{s1}, Btu/lb.

H_{L2} = enthalpy of salt water at t_{s2}, Btu/lb.

Q_c = heat transfer rate through membrane by conduction, Btu/hr.

V = mass transfer rate of water vapor through membrane, lb./hr.

H_v = enthalpy of water vapor at $(t_{s1} + t_{s2})/2$, Btu/lb.

Also assume that heat loss to the atmosphere is negligible.

In considering the solution on the salt water side, the mass balance is

$$W_{s1} = W_{s2} + V \tag{3-1}$$

or

$$W_{s2} = W_{s1} - V \tag{3-2}$$

the heat balance is

$$W_{s1}H_{L1} = W_{s2}H_{L2} + VH_v + Q_c \tag{3-3}$$

or

$$(W_{s1}H_{L1} - W_{s2}H_{L2}) = VH_v + Q_c \tag{3-4}$$

$$Q_t = Q_v + Q_c \tag{3-5}$$

$Q_t = (W_{s1}H_{L1} - W_{s2}H_{L2})$, total heat transfer rate, Btu/hr. $Q_v = VH_v$, heat transfer rate due to enthalpy transport of water vapor, Btu/hr. From Eq. (3-2), (3-4) and (3-5) one gets

$$Q_c = W_{s1}H_{L1} - (W_{s1} - V)H_{L2} - VH_v \tag{3-6}$$

Over-all Mass Transfer Coefficient: K_m was calculated by Eq. (2-26), or

$$K_m = \frac{V}{A\Delta p_m} \qquad (3\text{-}7)$$

where A is the surface area of the membrane, ft.^{2}, and

$$\Delta p_m = \frac{(p_{s1}-p_{f2})-(p_{s2}-p_{f1})}{\ln(p_{s1}-p_{f2})/(p_{s2}-p_{f1})} \qquad (3\text{-}8)$$

In this calculation

$A = 0.288$ ft.^{2}

$p_{s1} = 0.96$ x(vapor pressure in. Hg of pure water at t_{s1}), where 0.96 was used as activity of water in the 7% salt solution.

$p_{s2} = 0.96$ x(vapor pressure in in. Hg of pure water at t_{s2})

Over-All Heat Transfer Coefficient: U was calculated by Eq. (2-28), or

$$U = \frac{Q_c}{A\Delta t_m} \qquad (3\text{-}9)$$

where

$$\Delta t_m = \frac{(t_{s1}-t_{f2})-(t_{s2}-t_{f1})}{\ln(t_{s1}-t_{f2})/(t_{s2}-t_{f1})} \qquad (3\text{-}10)$$

IV. DISCUSSION

A. Equipment:

The variations of operating conditions in the developed equipment were restricted by the materials and apparatus that were available. The system pressure was built up by the compressed air which was supplied by the existing air line in the laboratory at 80 psig. However, the pressure regulation was unstable between the range of 60 to 80 psig. The second restriction on the operating pressure was caused by leakage of the pump at pressures over 40 psig.

The capacities of the pumps available were very low and a high flow rate operation could not be achieved, so the effect of flow rate on transfer properties was difficult to investigate.

The maximum operating temperature was essentially controlled by the operating pressure. It was planned to raise the temperature to near the boiling point of the salt water, but the instability of the liquid levels due to the generation of bubbles prevented this. The highest temperatures achieved in these experiments were as follows:

180 °F	at	14.7 psia
195 °F	at	24.7 psia
210 °F	at	34.7 psia
235 °F	at	44.7 psia

These temperatures are much lower than the boiling points of the salt water at these pressures. It was found that low flow rates caused the liquid levels to be unstable at temperatures near boiling point.

The membrane made by the procedure described on page 31 contains about 2.0 grams of teflon per 6.6 grams of fiberglas. The water repellent character had been tested by pressure and was found to fail at a pressure difference above 6 or 7 in. Hg. This means that this pressure difference will cause the liquid on the surface of the membrane to penetrate into the membrane. Thus compressed air must first be introduced into the Membrane-Evaporator-Condenser before any fluid coming in under pressure. When various pressure conditions are needed during the operation, the changes of pressure can only be achieved by reducing the pressure. Otherwise, increasing pressure during the operation might cause penetration of liquid into the membrane.

B. Experimental Data and Results:

Data and results are tabulated in Appendix II. Data in Table I to Table III were taken before satisfactory equipment was developed and data in Table IV to Table VII were taken with the final version of the equipment and are considered more accurate. Tables VIII and IX were used for correlations of the over-all resistance, $1/K_m$, but were apparently unsatisfactory for evaluation of heat transfer coefficients, since some values of the over-all heat transfer coefficients calculated from the experimental data were negative. Appendix III shows a sample computer program for calculating the over-all mass and heat transfer coefficients.

From the results, it was found that the over-all mass transfer coefficients have values between 0.05 and 0.2 (lb./hr.sq.ft.in.Hg), and the over-all heat transfer coefficients, though they were considered unsatisfactory, have average values between 10 and 20 (Btu/hr.sq.ft.°F), depending on operating conditions.

Some of the data were analyzed by using the least-squares approximating technique (See Appendix IV). The equation obtained for the best fit of these data is (See Fig. IV-1)

$$F_1 = \frac{1}{K_m} = 0.102 \left(\frac{1}{G^{0.3}}\right)\frac{\Delta P_m}{\Delta t_m}\Delta H_v + 516.5 \left(\frac{1}{G^{0.3}}\right)\frac{P}{\bar{T}} + 8.87 \frac{1}{G^{0.3}} \qquad (4\text{-}1)$$

S_E = root mean square of deviations of $1/K_m$ about correlation function = 1.235

where G = mass flow rate of salt water, lb./hr.sq.ft.

ΔP_m = log-mean pressure drop, calculated by Eq. (3-8), in.Hg

Δt_m = log-mean temperature drop, calculated by Eq. (3-10), °F

ΔH_v = latent heat of vaporization, Btu/lb.

P = total pressure, in.Hg

$\bar{T}$ = average absolute temperature, °R

The first and second terms have a theoretical basis (See Eq. (2-30)), but are modified with the flow rate, the last term is used for correction of the liquid film resistance. The flow rate has little effect compared with other factors, since it appears with 0.3 power.

In order to understand the effect of p_{BM}, log-mean partial pressure of air, the data were also correlated with p_{BM}. Fig. IV-2 shows the result of this analysis. It is observed that the over-all mass transfer resistance, $1/K_m$, increases linearly with p_{BM}. The equation obtained is

$$F_2 = \frac{1}{K_m} = 2.611 + 0.151\ p_{BM} \qquad (4\text{-}2)$$

$$S_E = 2.038$$

having a slope of 0.151, which means the effect of p_{BM} on $1/K_m$ is small.

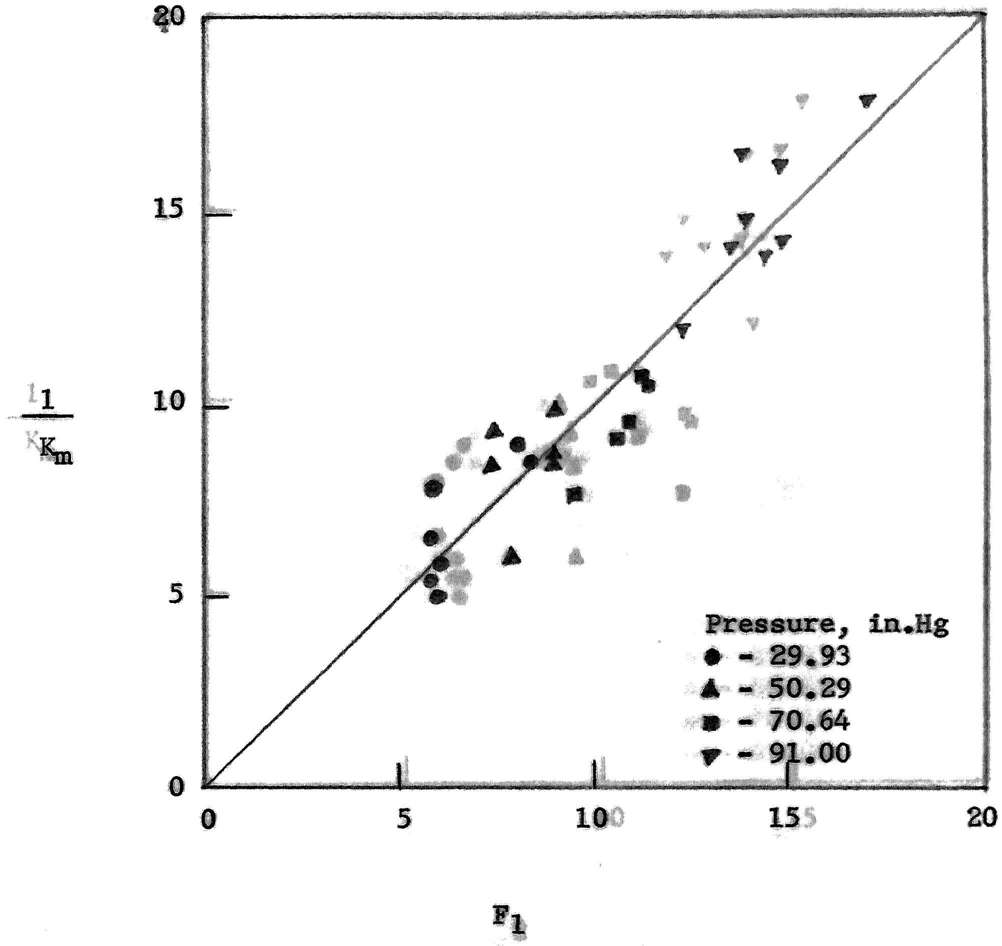
Fig. IV-3 indicates the result of another least-squares equation that also can fit the experimental data, this equation is

$$F_3 = \frac{1}{K_m} = -11.04\ \frac{p_{BM}}{P} + 81.3\ \frac{1}{G^{0.3}} + 92.41\ \frac{P}{\bar{T}} \qquad (4\text{-}3)$$

$$S_E = 1.318$$

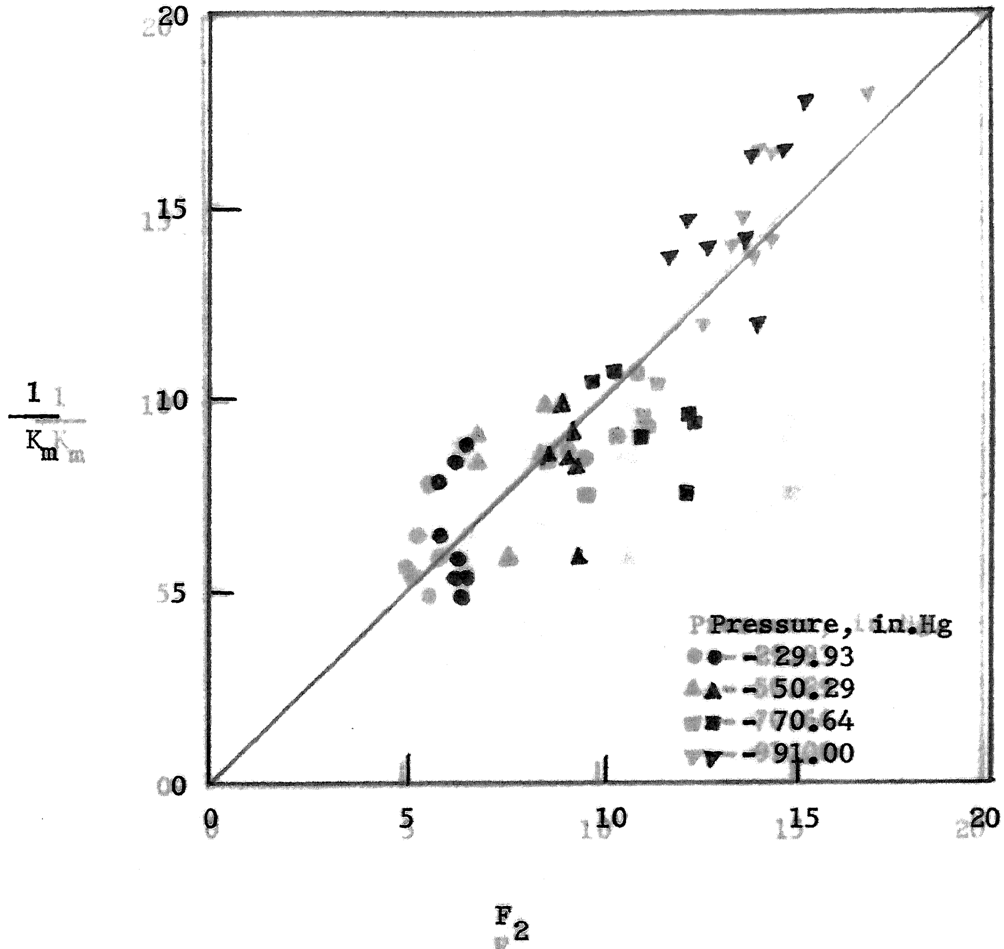
It shows the effect of P/p_{BM}, the reciprocal of the drift factor, on $1/K_m$.

All the data and figures have shown that the over-all mass transfer resistance increases with the total pressure.



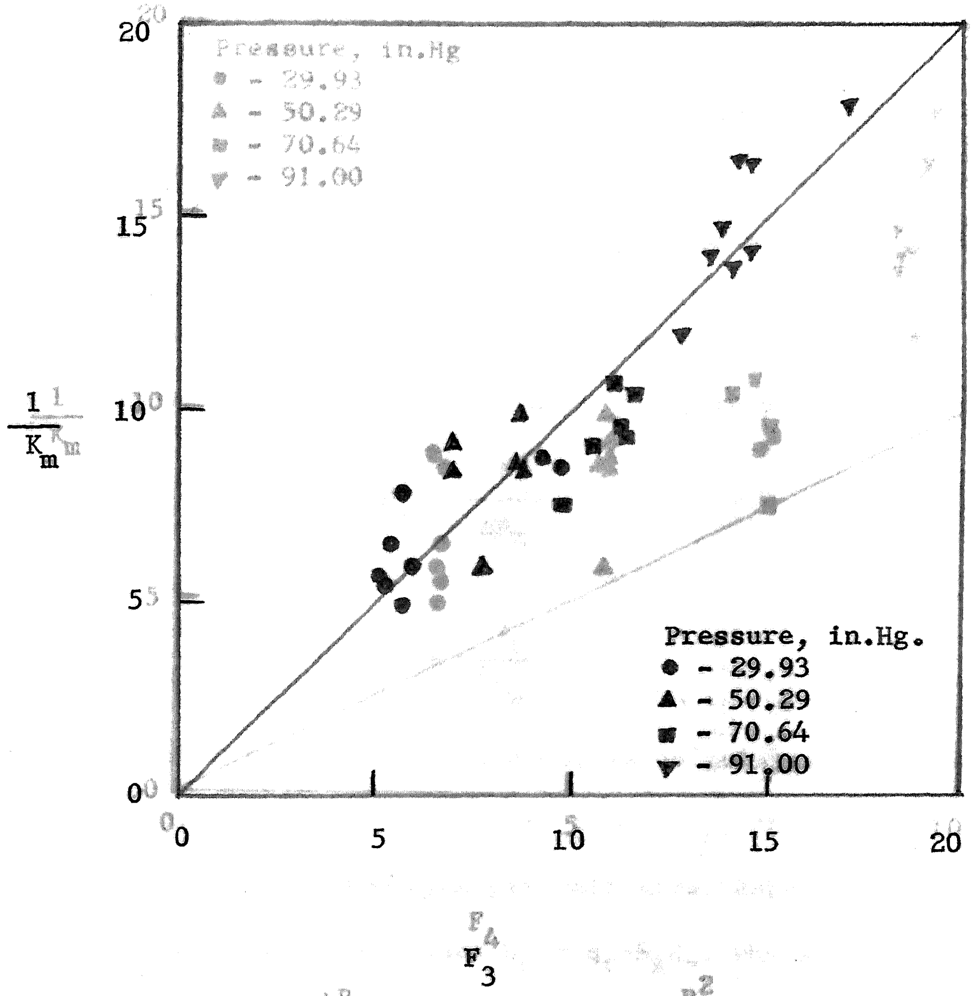
$$F_1 = 0.102 \frac{1}{G^{0.3}} \frac{\Delta P}{\Delta T} \Delta H_v + 516.5 \frac{1}{G^{0.3}} \frac{P}{T} + 8.87 \frac{1}{G^{0.3}}$$

Fig. IV-1 Plot of $1/K_m$ Against F_1



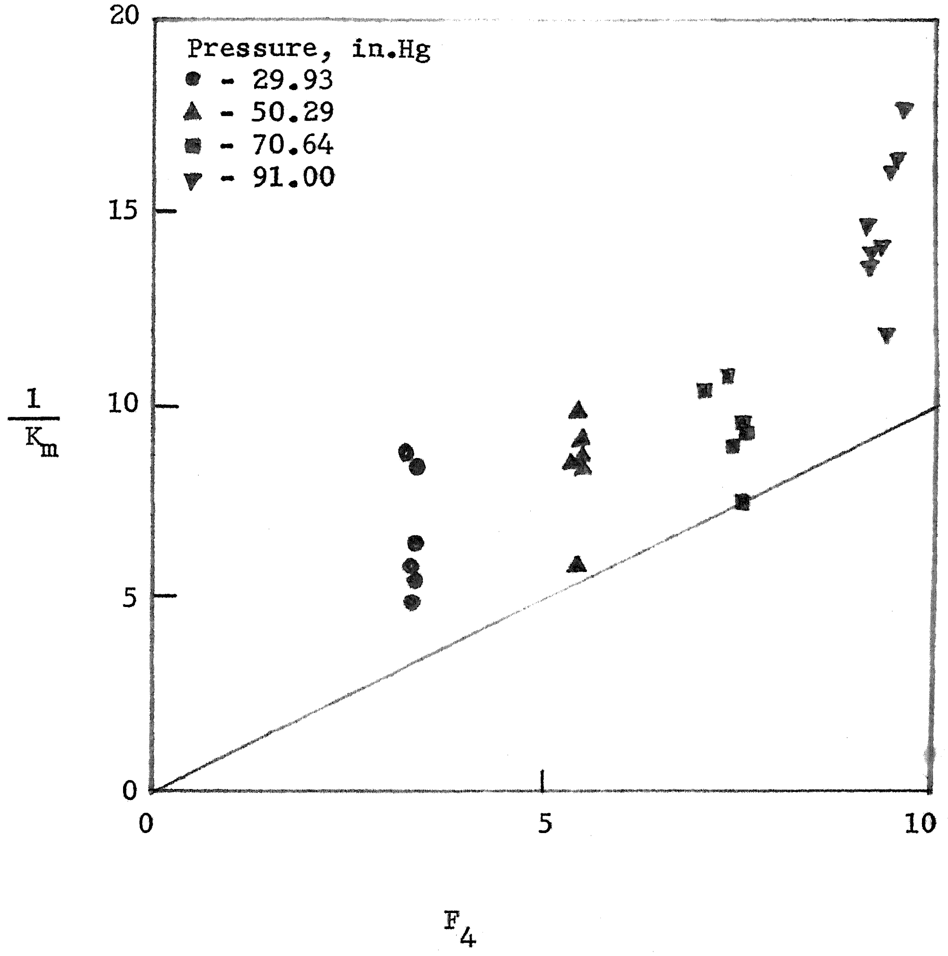
$$F_2 = 2.611 + 0.151\ P_{BM}$$

Fig. IV-2 Plot of $1/K_m$ Against F_2



$$F_3 = -\ 11.04 \frac{P_{BM}}{P} + 81.3 \frac{L}{G^{0.3}} + 92.41 \frac{P}{\bar{T}}$$

Fig. IV-3 Plot of $1/K_m$ Against F_3



$$F_4^* = 0.00435 \frac{\Delta P}{\Delta T} \Delta H_v + 5.21 \frac{P^2}{(2P + P_s + P_f)\sqrt{T}}$$

Fig. IV-4 Plot of $1/K_m$ Against F_4

*This correlation function is obtained by Yeh (23)

C. Explanation of Errors:

The experimental results tabulated in Appendix II show that the over-all mass transfer coefficients are lower than predicted by Yeh's (23) equation (See Fig. IV-4) and the over-all heat transfer coefficients are also low compared with his results. Some negative values of the over-all heat transfer coefficient were found, especially in the earlier runs. The deviations and errors can be explained as follows:

In this investigation, the over-all mass and heat transfer coefficients were estimated by Eq. (3-7) and (3-9), respectively, or

$$K_m = \frac{N_A}{\Delta p_m} \qquad (4\text{-}4)$$

and

$$U = \frac{q_c}{\Delta t_m} \qquad (4\text{-}5)$$

N_A, the mass transfer rate per unit area, is calculated based on the volume of the salt water drawn per unit time. q_c, the conductive heat transfer rate through the membrane per unit area, depends on the total heat transfer rate and N_A, and thus $q_c = q_t - N_A H_v$, where H_v is the enthalpy of water vapor leaving the salt water surface. If N_A and q_c calculated from the experimental data are accurate, the errors of K_m and U must be attributed to the errors of Δp_m and Δt_m, the log-mean partial pressure of water vapor and temperature drops across the membrane, respectively. The accuracies of Δp_m and Δt_m depend on the temperature curve along the longitudinal direction in the two channels.

In order to examine these temperature distrubutions, one experimental run was made. Two additional thermocouples were placed near the bottoms of the two channels (point 3 and 3' in Fig. IV-5). Assume point 1, 2, 3 and 1', 2', 3' indicate the inlet, outlet, and middle points of the salt water and fresh water channels, respectively, temperatures for these points were measured during the operation at approximately steady state. The data are listed in the following table:

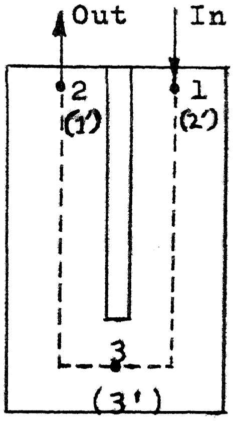
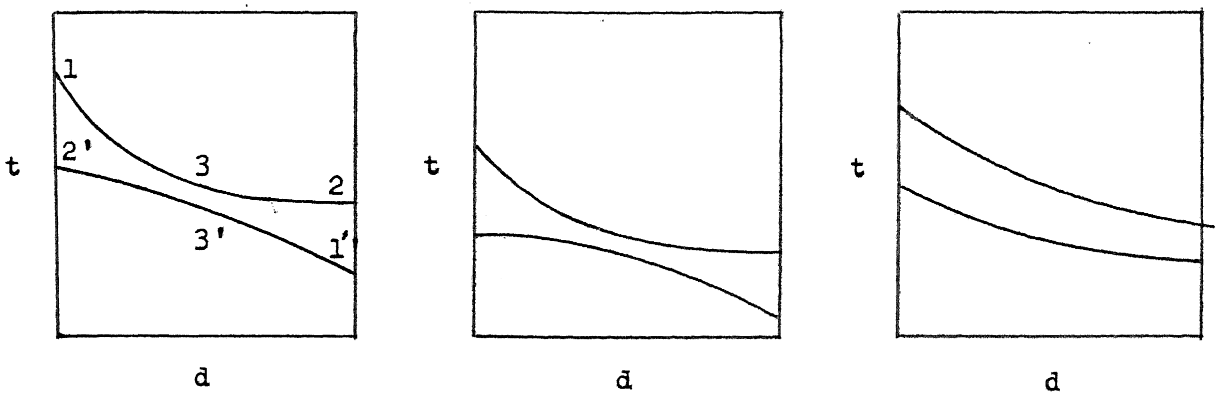


Fig. IV-5 Locations of Thermocouples in Channels

Data of Temperatures in Channels

Run	Salt water temp. °F			Fresh water temp. °F		
no.	pt.1	pt.3	pt.2	pt.1'	pt.3'	pt.2'
1	168.4	137.1	136.6	114.3	132.3	143.3
	169.6	137.9	137.9	116.9	133.6	144.8
	169.9	139.0	139.0	117.8	134.1	145.6
2	146.8	127.3	125.6	106.3	124.7	128.6
	148.0	125.6	122.6	105.5	123.1	127.8
	148.0	125.2	122.2	105.1	122.6	127.8

The above data were plotted in Fig. IV-6, which gives the trend of temperature distributions along the longitudinal direction in the channels.



Run 1 Run 2 Normal Curve

Fig. IV-6 Temperatures in U Channels

Either of the first two diagrams shows that the temperature difference at the middle of the channels is much smaller than those at the ends. This is probably due to the slow flow rate and high convective heat transmission at the bottoms of the channels and the hot and cold fluids in the two arms of the same channel were then mixed in a major part of the channels. In addition, heat transfer may occur from one arm of either channel to the other arm of the same channel, which would also tend to produce the effect shown in Fig. IV-6. Thus Δt_m and Δp_m calculated based on the inlet and outlet temperature differences must be larger than the actual values. This is the main reason why the over-all mass and heat transfer coefficients become smaller than the expected values.

Furthermore, some heat could transfer into the aluminum plate from the hot entrance due to the high heat conductivity of the aluminum plate, and then transfer into the fluid especially within the region of the cold arm of the channel. When this transfer of heat becomes significant, q_c calculated by Eq. (3-6) would be too low or even negative.

According to the above discussion, the results of this investigation are not sufficiently accurate to be used for prediction of mass and heat transfer coefficients. However, results do show that the method is technically feasible, and the correlations indicate the results are consistent and provide indications of the effects of pressures and flow rates.

D. Alternate Designs of Apparatus:

The main disadvantages of the U channel type apparatus used in this work are:

(1) Difficulties in estimating the heat loss to the atmosphere.

(2) Erratic temperature distributions in the channels as shown in Fig. IV-6.

In an attempt to improve the design, two alternate types of apparatus are suggested as follows:

1. Double Pipe Exchanger Type: This apparatus is essentially two concentric pipes with one fluid (hot salt water) flowing through the center membrane tube while the other fluid (cold fresh water) moves countercurrently in the annular space. The transfer area part of the center tube is made of membrane with a noncorrosive screen supporting it. The screen is welded on the center pipe at its two ends and covered by the membrane in a manner such that no salt water can leak through the connecting ends. A pressure balance air pipe is installed above the apparatus and connected with the two pipes near the entrance of the salt water and the exit of the fresh water (Fig. IV-7).

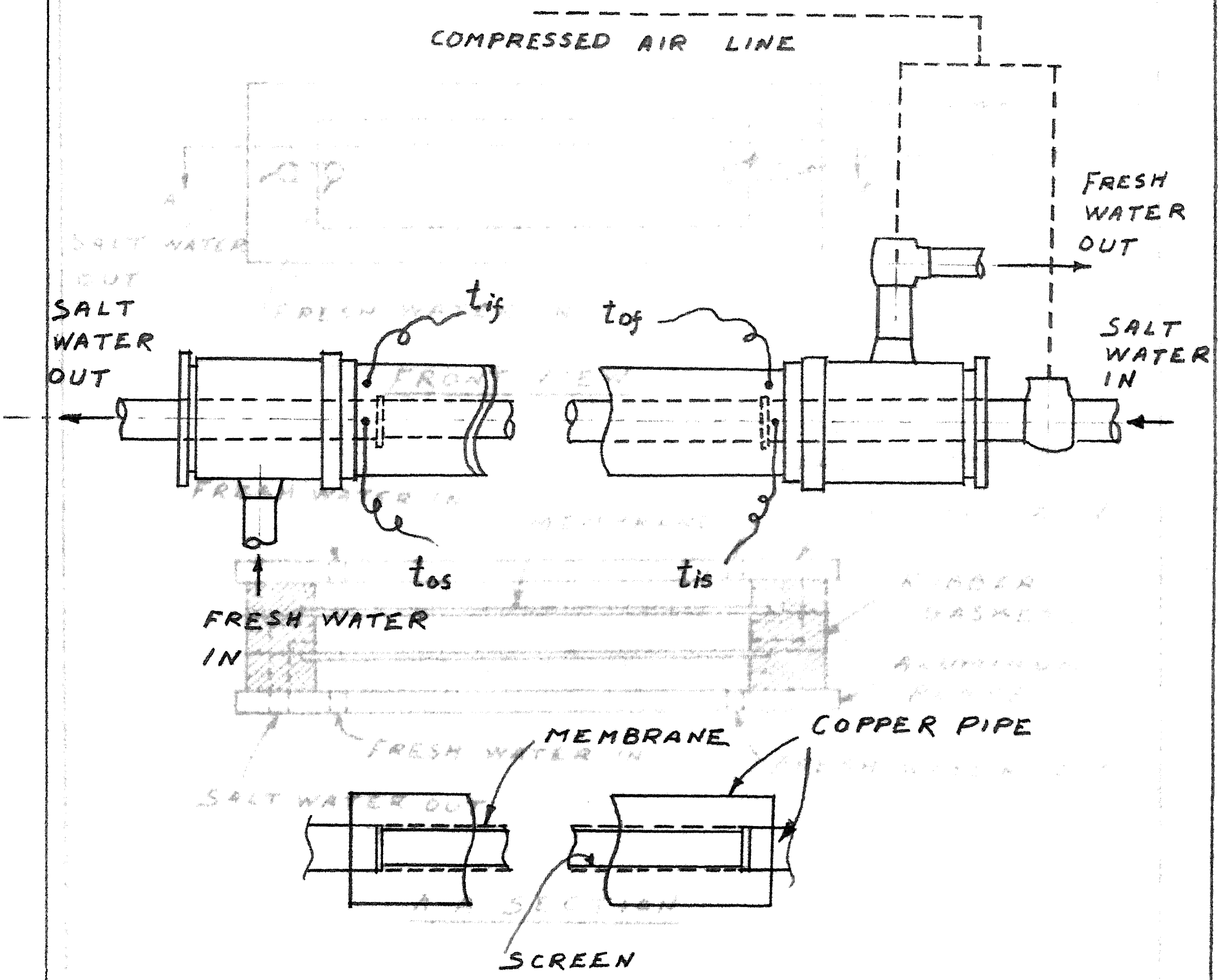


Fig. IV-7 Double Pipe Exchanger Type Apparatus

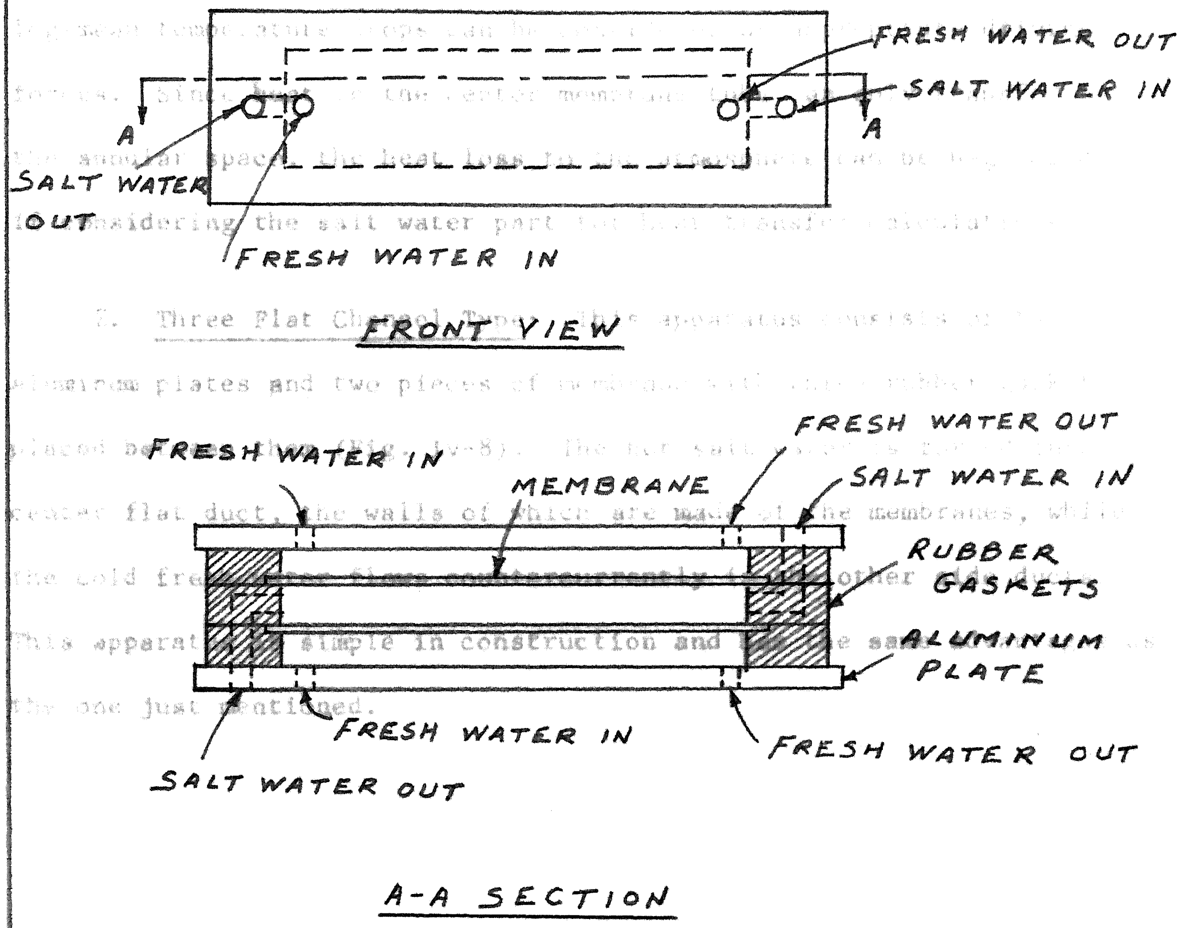


Fig. IV-8 Three Flat Channel Type Apparatus

For this apparatus, the temperature variation along the channels should be similar to those in a countercurrent heat exchangers, and log-mean temperature drops can be considered as appropriate driving forces. Since heat in the center membrane tube can only transfer to the annular space, the heat loss to the atmosphere can be neglected if considering the salt water part for heat transfer calculations.

2. Three Flat Channel Type: This apparatus consists of two aluminum plates and two pieces of membrane with three rubber gaskets placed between them (Fig. IV-8). The hot salt water is forced into center flat duct, the walls of which are made of the membranes, while the cold fresh water flows countercurrently in the other side ducts. This apparatus is simple in construction and has the same advantages as the one just mentioned.

V. CONCLUSIONS

This investigation has led to the following conclusions:

(1) The method of evaporation through porous water-repellent membranes by a continuous countercurrent flow process has been demonstrated to be technically feasible. However, a strong and more efficient membrane would be desirable for commercial application.

(2) The final version of the equipment can be used for the study of simultaneous heat and mass transfer through membranes for a limited range of pressure and flow rate, but calculated transfer coefficients are probably lower than true values. Improved designs for the membrane apparatus have been suggested in order to secure more satisfactory experimental results.

(3) The resistance for mass transfer is primarily inside the membrane. The total pressure, the flow rate and the log-mean partial pressure of air have effects on the over-all mass transfer coefficient. The over-all mass transfer resistance increases strongly with the total pressure and slightly with the log-mean partial pressure of air. The resistance decreases slightly with flow rate under the low flow rates investigated.

VI. RECOMMENDATIONS

From the results of this experimental work, recommendations for extending this study are as follows:

(1) For further improvement of the experiment two alternate membrane apparatus (See Fig. IV-7 and Fig. IV-8) are recommended. An accurate flow meter is needed to be installed on the equipment, because the flow rate is an important factor in heat transfer calculations.

(2) Larger variations of operating conditions should be used in this study. In order to understand the transport phenomena in a turbulent flow region, larger capacity pumps are needed.

(3) Better membrane preparation techniques should be investigated to improve the qualities of the membrane for commercial applications.

VII. APPENDICES

APPENDIX I

VAPOR PRESSURE OF WATER

The vapor pressure of water at the salt water and fresh water temperatures are obtained from the equation (12)

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

where

p = vapor pressure in atm.

p_c = 218.167 atm.

$T = t°C + 273.16$

$x = T_c - T$

$T_c = 647.27$

$a' = 3.2437814$

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

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

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

APPENDIX II

DATA AND RESULTS

The experimental data taken during the investigation and the results obtained are included in this appendix.

TABLE I

DATA AND RESULTS

Run No.	Pressure in.Hg	Flow Rate lb./hr. sq.ft.	Salt Water Temperature Inlet °F	Salt Water Temperature Outlet °F	Fresh Water Temperature Inlet °F	Fresh Water Temperature Outlet °F	Mass Transfer Rate lb./hr. sq.ft.	Heat Transfer Rate Btu/hr. sq.ft.	K_m lb./hr. sq.ft. in.Hg	U Btu/hr. sq.ft. °F
1	29.93	127.08	119.04	100.14	94.30	96.36	0.04	3.51	0.05	0.28
2	29.93	127.08	116.61	100.98	95.65	96.90	0.04	-7.91	0.07	-0.72
	29.93	169.52	103.50	97.10	91.22	95.60	0.02	-0.42	0.06	-0.06
	29.93	169.52	102.35	96.26	90.11	94.80	0.02	-3.64	0.07	-0.53
	29.93	169.52	102.98	96.76	90.70	95.34	0.02	3.13	0.05	0.46
	29.93	169.52	102.63	96.54	90.48	95.03	0.02	-0.46	0.06	-0.07
	29.93	169.52	102.58	96.39	90.17	94.03	0.02	-2.32	0.06	-0.32
3	29.93	277.02	146.53	138.76	131.18	134.78	0.09	-50.55	0.07	-5.31
	29.93	277.02	149.77	139.45	130.62	135.30	0.08	-33.90	0.06	-2.97
4	29.93	406.64	148.52	139.84	132.69	136.98	0.12	-54.36	0.10	-5.93
	29.93	406.64	147.04	138.51	130.04	132.96	0.16	-104.45	0.12	-9.46
	29.93	406.64	147.07	137.79	129.04	131.10	0.17	-106.95	0.11	-8.91
	29.93	406.64	147.01	138.03	129.32	131.85	0.16	-97.40	0.11	-8.37
5	29.93	406.64	146.85	138.01	129.47	132.78	0.16	-98.51	0.11	-8.90
	29.93	406.64	152.96	143.67	132.89	138.94	0.16	-90.55	0.09	-7.34
	29.93	406.64	154.59	146.48	137.90	141.22	0.18	-120.56	0.11	-11.16
	29.93	406.64	154.92	146.92	138.95	141.20	0.17	-115.31	0.11	-10.90
	29.93	406.64	155.06	146.71	139.43	142.67	0.18	-124.41	0.13	-12.95

TABLE II

DATA AND RESULTS

Run No.	Pressure in.Hg	Flow Rate lb./hr. sq.ft.	Salt Water Temperature Inlet °F	Salt Water Temperature Outlet °F	Fresh Water Temperature Inlet °F	Fresh Water Temperature Outlet °F	Mass Transfer Rate lb./hr. sq.ft.	Heat Transfer Rate Btu/hr. sq.ft.	K_m lb./hr. sq.ft. in.Hg	U Btu/hr. sq.ft. °F
6	29.93	406.64	130.85	118.23	112.69	119.52	0.13	-43.22	0.20	-5.34
	29.93	406.64	129.56	116.94	109.94	118.23	0.12	-35.72	0.17	-3.97
7	29.93	406.64	140.38	124.80	117.68	124.33	0.22	-107.69	0.19	-9.80
	29.93	406.64	139.92	125.45	118.11	118.80	0.19	-91.45	0.15	-7.01
	29.93	406.64	139.66	125.75	118.58	118.46	0.19	-93.99	0.15	-7.26
	29.93	406.64	139.62	126.14	118.58	118.71	0.23	-136.25	0.17	-10.39
8	29.93	660.79	144.37	131.15	120.42	123.51	0.33	-178.36	0.19	-11.70
	29.93	660.79	144.99	131.50	120.86	123.77	0.32	-167.33	0.18	-10.92
	29.93	660.79	145.28	130.80	120.15	123.63	0.34	-171.31	0.19	-11.05
	29.93	660.79	146.11	130.75	120.23	123.79	0.32	-145.21	0.18	-9.26
9	29.93	991.19	142.46	129.94	114.56	122.72	0.35	-135.69	0.18	-7.77
	29.93	991.19	142.48	130.78	115.53	123.86	0.39	-189.18	0.21	-11.21
	29.93	991.19	146.03	134.68	117.12	125.41	0.36	-163.53	0.16	-8.58
	29.93	991.19	147.25	134.86	118.55	126.53	0.42	-207.23	0.19	-11.25
	29.93	991.19	146.88	135.69	119.38	127.49	0.41	-220.57	0.19	-12.39
	29.93	991.19	147.17	135.33	119.28	127.30	0.40	-193.49	0.18	-10.81
	29.93	991.19	147.61	134.80	118.57	126.94	0.40	-176.24	0.18	-9.60

TABLE III

DATA AND RESULTS

Run No.	Pressure in.Hg	Flow Rate lb./hr. sq.ft.	Salt Water Temperature Inlet °F	Salt Water Temperature Outlet °F	Fresh Water Temperature Inlet °F	Fresh Water Temperature Outlet °F	Mass Transfer Rate lb./hr. sq.ft.	Heat Transfer Rate Btu/hr. sq.ft.	K_m lb./hr. sq.ft. in.Hg	U Btu/hr. sq.ft. °F
10	91.00	1715.52	229.12	205.98	193.76	202.10	0.73	-1.88	0.07	-0.10
	91.00	1715.52	235.10	208.19	196.39	204.53	0.77	79.36	0.07	4.03
	91.00	1715.52	235.25	209.02	196.46	205.41	0.85	-17.64	0.07	-0.88
	91.00	1715.52	236.35	210.09	198.10	206.13	0.85	-15.92	0.07	-0.81
	91.00	1715.52	237.69	210.85	198.52	206.66	0.83	24.47	0.07	1.21
	91.00	1715.52	223.98	200.00	189.38	195.85	0.59	164.08	0.07	9.13
	91.00	1715.52	224.82	201.64	191.44	197.22	0.68	46.50	0.08	2.66
	91.00	1715.52	236.92	211.38	199.51	207.46	0.84	-30.07	0.07	-1.55
11	29.93	277.02	149.42	140.13	134.35	138.30	0.05	-7.92	0.05	-0.97
	29.93	277.02	148.73	139.97	131.77	136.23	0.09	-52.53	0.07	-5.15
12	29.93	406.64	146.82	138.20	129.62	132.83	0.16	-100.03	0.11	-9.04
	29.93	406.64	155.20	147.35	139.84	142.05	0.18	-127.97	0.12	-12.71
13	29.93	991.19	143.87	132.34	116.58	124.70	0.41	-207.56	0.20	-11.92
	29.93	991.19	147.66	135.97	119.52	127.47	0.39	-188.18	0.17	-10.31
14	29.93	1245.34	149.98	137.43	119.13	129.14	0.47	-192.63	0.19	-9.86
	29.93	1245.34	150.33	137.82	119.52	129.66	0.47	-193.51	0.19	-9.94
15	70.64	1715.52	207.30	197.22	189.22	194.17	0.33	-10.35	0.08	-1.00
	70.64	1715.52	210.54	193.98	182.87	190.56	0.61	-83.63	0.10	-5.53

TABLE IV

DATA AND RESULTS

Run No.	Pressure in.Hg	Flow Rate lb./hr. sq.ft.	Salt Water Temperature Inlet °F	Salt Water Temperature Outlet °F	Fresh Water Temperature Inlet °F	Fresh Water Temperature Outlet °F	Mass Transfer Rate lb./hr. sq.ft.	Heat Transfer Rate Btu/hr. sq.ft.	K_m lb./hr. sq.ft. in.Hg	U Btu/hr. sq.ft. °F
16	29.93	991.19	131.43	111.68	101.51	111.38	0.24	109.90	0.20	7.55
	29.93	991.19	132.75	113.74	103.22	113.31	0.23	97.77	0.20	6.73
	29.93	991.19	133.69	114.85	104.42	114.55	0.24	84.33	0.20	5.88
	29.93	991.19	173.55	139.67	132.55	144.43	0.39	208.00	0.14	13.32
17	29.93	991.19	175.83	143.86	137.57	148.24	0.39	175.07	0.14	12.15
	29.93	991.19	177.36	146.14	139.94	149.95	0.38	169.82	0.14	11.90
	29.93	991.19	179.00	148.74	142.27	151.79	0.41	122.38	0.14	8.47
18	29.93	1715.52	168.56	150.48	139.26	149.72	0.39	160.73	0.14	10.93
	29.93	1715.52	172.74	153.03	142.11	152.58	0.44	170.17	0.15	11.29
	29.93	1715.52	173.70	153.91	142.11	153.34	0.40	205.18	0.13	13.08
	29.93	1715.52	170.65	151.85	140.97	151.32	0.44	137.01	0.16	9.32
	29.93	1715.52	174.27	153.34	141.54	152.39	0.42	221.77	0.13	13.59
	50.29	991.19	171.34	149.27	141.36	148.43	0.27	122.61	0.10	8.69
19	50.29	991.19	167.35	149.16	141.48	149.09	0.26	61.10	0.12	5.00
	50.29	1245.34	162.10	132.50	115.03	131.89	0.54	110.88	0.17	4.77
20	50.29	1245.34	193.02	151.12	135.57	156.49	0.68	256.45	0.12	10.44
	50.29	1715.52	159.17	148.29	135.83	143.72	0.25	84.32	0.11	6.07
21	50.29	1715.52	158.94	146.77	135.61	142.96	0.26	113.76	0.12	8.48

TABLE V

DATA AND RESULTS

Run No.	Pressure in.Hg	Flow Rate lb./hr. sq.ft.	Salt Water Temperature Inlet °F	Salt Water Temperature Outlet °F	Fresh Water Temperature Inlet °F	Fresh Water Temperature Outlet °F	Mass Transfer Rate lb./hr. sq.ft.	Heat Transfer Rate Btu/hr. sq.ft.	K_m lb./hr. sq.ft. in.Hg	U Btu/hr. sq.ft. °F
22	50.29	660.79	141.11	113.58	102.64	115.94	0.26	58.27	0.17	3.41
	50.29	660.79	142.45	115.08	103.92	117.01	0.31	3.69	0.19	0.21
23	50.29	991.19	169.28	149.57	141.89	148.35	0.27	83.74	0.11	6.34
	50.29	991.19	168.27	149.24	141.52	148.10	0.24	92.71	0.10	7.15
24	50.29	1245.34	136.54	117.65	105.90	115.55	0.29	121.64	0.21	7.64
	50.29	1245.34	174.54	142.16	124.63	142.92	0.57	146.66	0.14	6.14
25	50.29	1715.52	159.17	147.72	136.04	143.53	0.34	11.09	0.15	0.82
	50.29	1715.52	158.63	147.15	135.05	142.77	0.24	109.68	0.11	7.90
26	70.64	991.19	163.12	141.80	131.30	138.75	0.25	124.74	0.10	7.57
	70.64	991.19	163.23	141.92	132.30	139.83	0.25	130.47	0.10	8.41
	70.64	991.19	161.82	141.62	132.72	139.64	0.24	116.57	0.11	8.02
	70.64	991.19	160.19	141.66	133.15	139.94	0.23	94.46	0.11	6.98
	70.64	991.19	161.78	141.85	132.94	139.71	0.24	111.84	0.11	7.71
	70.64	991.19	160.95	141.35	133.02	139.26	0.23	113.44	0.11	8.13
27	70.64	1715.52	180.65	151.33	125.30	139.60	0.84	61.48	0.13	1.86
	70.64	1715.52	173.99	142.38	116.08	128.09	0.93	31.39	0.17	0.89
	70.64	1715.52	185.98	157.61	131.95	146.19	0.85	18.79	0.12	0.58

TABLE VI

DATA AND RESULTS

Run No.	Pressure in.Hg	Flow Rate lb./hr. sq.ft.	Salt Water Temperature		Fresh Water Temperature		Mass Transfer Rate lb./hr. sq.ft.	Heat Transfer Rate Btu/hr. sq.ft.	K_m lb./hr. sq.ft. in.Hg	U Btu/hr. sq.ft. °F
			Inlet °F	Outlet °F	Inlet °F	Outlet °F				
28	70.64	1715.52	199.80	167.46	149.97	165.94	0.70	298.90	0.10	12.06
	70.64	1715.52	202.65	170.77	153.96	169.56	0.65	333.48	0.09	13.87
	70.64	1715.52	208.16	174.31	157.96	173.55	0.80	248.73	0.10	10.21
	70.64	1715.52	209.69	176.02	159.86	173.93	0.79	256.79	0.09	10.41
29	91.00	406.64	162.45	140.18	134.62	141.51	0.13	26.19	0.08	2.26
	91.00	406.64	170.82	141.89	134.62	141.51	0.09	118.88	0.03	7.52
30	91.00	991.19	187.95	148.36	130.12	146.08	0.36	344.40	0.06	12.11
	91.00	991.19	201.27	156.93	143.22	154.64	0.52	266.86	0.07	9.93
	91.00	991.19	203.17	160.16	146.27	155.78	0.52	246.38	0.07	9.03
	91.00	991.19	214.59	163.59	148.93	163.97	0.46	449.26	0.05	15.48
	91.00	991.19	219.34	169.30	154.26	169.68	0.65	239.94	0.06	8.28
	91.00	991.19	226.58	171.96	158.26	171.96	0.72	250.61	0.06	8.47
	91.00	991.19	214.78	176.22	165.49	174.62	0.66	29.27	0.08	1.31
	91.00	991.19	211.35	177.86	167.77	177.29	0.45	149.11	0.06	7.57
	91.00	991.19	211.92	179.57	170.44	178.81	0.43	147.76	0.06	7.94
	91.00	991.19	214.78	181.86	171.96	180.71	0.46	132.42	0.06	6.77

TABLE VII

DATA AND RESULTS

Run No.	Pressure in.Hg	Flow Rate lb./hr. sq.ft.	Salt Water Temperature Inlet °F	Salt Water Temperature Outlet °F	Fresh Water Temperature Inlet °F	Fresh Water Temperature Outlet °F	Mass Transfer Rate lb./hr. sq.ft.	Heat Transfer Rate Btu/hr. sq.ft.	K_m lb./hr. sq.ft. in.Hg	U Btu/hr. sq.ft. °F
31	29.93	991.19	176.51	125.16	112.29	144.53	0.41	492.25	0.12	23.45
	29.93	991.19	177.56	129.77	113.47	147.48	0.42	424.09	0.11	18.86
	29.93	991.19	183.27	131.48	115.61	149.39	0.47	438.61	0.11	18.47
	29.93	991.19	180.98	133.20	115.19	129.34	0.46	383.61	0.09	12.01
32	29.93	1715.52	168.42	136.63	114.33	143.29	0.45	528.96	0.12	22.33
	29.93	1715.52	169.56	137.92	116.90	144.82	0.44	531.54	0.12	23.28
	29.93	1715.52	169.94	139.11	117.76	145.58	0.47	478.96	0.13	20.99
	29.93	1715.52	168.87	139.93	118.69	144.50	0.51	373.67	0.14	16.41
33	29.93	660.79	148.31	126.84	107.54	129.41	0.43	-181.16	0.20	-9.49
	29.93	660.79	146.79	125.55	106.25	128.55	0.37	-130.43	0.18	-6.95
	29.93	660.79	147.99	122.62	105.46	127.77	0.36	-68.53	0.18	-3.67
	29.93	660.79	147.99	122.19	105.03	127.77	0.35	-56.78	0.18	-3.04

TABLE VIII

DATA AND RESULTS

Run No.	Pressure in.Hg	Flow Rate lb./hr. sq.ft.	Salt Water Temperature Inlet °F	Salt Water Temperature Outlet °F	Fresh Water Temperature Inlet °F	Fresh Water Temperature Outlet °F	Mass Transfer Rate lb./hr. sq.ft.	Heat Transfer Rate Btu/hr. sq.ft.	K_m lb./hr. sq.ft. in.Hg	U Btu/hr. sq.ft. °F
A	29.93	277.02	149.42	140.13	134.35	138.30	0.05	-7.92	0.05	-0.97
	29.93	277.02	148.73	139.97	131.77	136.23	0.09	-52.53	0.07	-5.15
	29.93	406.64	146.82	138.20	129.62	132.83	0.16	-100.03	0.11	-9.04
	29.93	406.64	155.20	147.35	139.84	142.05	0.18	-127.97	0.12	-12.71
	29.93	991.19	143.87	132.34	116.58	124.70	0.41	-207.56	0.20	-11.92
	29.93	991.19	147.66	135.97	119.52	127.47	0.39	-188.18	0.17	-10.31
	29.93	1245.34	149.98	137.43	119.13	129.14	0.47	-192.63	0.19	-9.86
	29.93	1245.34	150.33	137.82	119.52	129.66	0.47	-193.51	0.19	-9.94
	29.93	1715.52	170.65	151.85	140.97	151.32	0.44	137.01	0.16	9.32
	29.93	1715.52	174.27	153.34	141.54	152.39	0.42	221.77	0.13	13.59
B	50.29	991.19	171.34	149.27	141.36	148.43	0.27	122.61	0.10	8.69
	50.29	991.19	167.35	149.16	141.48	149.09	0.26	61.10	0.12	5.00
	50.29	1245.34	162.10	132.50	115.03	131.89	0.54	110.88	0.17	4.77
	50.29	1245.34	193.02	151.12	135.57	156.49	0.68	256.45	0.12	10.44
	50.29	1715.52	159.17	148.29	135.83	143.72	0.25	84.32	0.11	6.07
	50.29	1715.52	158.94	146.77	135.61	142.96	0.26	113.76	0.12	8.48

TABLE IX

DATA AND RESULTS

Run No.	Pressure in.Hg	Flow Rate lb./hr. sq.ft.	Salt Water Temperature Inlet °F	Salt Water Temperature Outlet °F	Fresh Water Temperature Inlet °F	Fresh Water Temperature Outlet °F	Mass Transfer Rate lb./hr. sq.ft.	Heat Transfer Rate Btu/hr. sq.ft.	K_m lb./hr. sq.ft. in.Hg	U Btu/hr. sq.ft. °F
C	70.64	991.19	161.78	141.85	132.94	139.71	0.24	111.84	0.11	7.71
	70.64	991.19	160.95	141.35	133.02	139.26	0.23	113.44	0.11	8.13
	70.64	1715.52	180.65	151.33	125.30	139.60	0.84	61.48	0.13	1.86
	70.64	1715.52	209.74	200.49	191.85	197.11	0.43	-130.83	0.10	-12.45
	70.64	1715.52	209.43	190.36	178.60	186.02	0.63	-28.56	0.09	-1.69
	70.64	1715.52	203.68	172.79	156.43	171.72	0.83	130.33	0.11	5.60
D	91.00	406.64	168.34	141.89	134.84	139.99	0.14	47.81	0.06	3.12
	91.00	991.19	198.03	153.39	135.48	150.84	0.45	346.56	0.06	11.47
	91.00	991.19	219.92	166.63	151.41	167.01	0.64	305.63	0.06	10.10
	91.00	991.19	210.78	176.72	167.58	175.58	0.49	120.78	0.07	6.25
	91.00	1715.52	197.15	179.53	168.22	174.50	0.44	105.05	0.08	6.44
	91.00	1715.52	218.77	196.96	186.87	192.58	0.55	133.68	0.07	7.92
	91.00	1715.52	226.65	202.10	192.01	198.67	0.61	165.92	0.07	9.46
	91.00	1715.52	234.83	207.04	194.48	202.86	0.86	18.19	0.07	0.88

APPENDIX III

COMPUTER PROGRAM

The program used for the computations described in this thesis is given in this appendix. The program was written in Fortran IV language and was run on an IBM system 360.

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LEVEL: 1JUL66                                  IBM OS/360 BASIC FORTRAN IV (E) COMPILATION

                C       PROGRAM FOR MASS AND HEAT TRANSFER CALCULATIONS
  S.0001                DIMENSION TSM(200),TFM(200),WH(200),DTM(200),HTC(200),DPM(200)
  S.0002                DIMENSION WTC(200),TM(200),WF(200),P1(200),DHV(200),WH1(200)
  S.0003                DIMENSION PSM(200),PFM(200)WF1(200),TM1(200)
  S.0004                J=1
  S.0005                A1=3.2438
  S.0006                A2=5.8683E-3
  S.0007                C=1.1702E-8
  S.0008                D=2.1878E-3
  S.0009                AR=0.288
  S.0010          110   READ(1,300)EMSI,EMSO,EMFI,EMFO,TCR,TIME,W,N
  S.0011                READ(1,401)FF,PP
  S.0012                EMSI=EMSI+TCR/24.49
  S.0013                EMSO=EMSO+TCR/24.49
  S.0014                EMFI=EMFI+TCR/24.49
  S.0015                EMFO=EMFO+TCR/24.49
  S.0016                IF(EMSI-2.450)220,220,330
  S.0017          220   TCSI=EMSI*24.49
  S.0018                GO TO 440
  S.0019          330   TCSI=60.0+(EMSI-2.450)*21.74
  S.0020          440   IF(EMSO-2.450)550,550,660
  S.0021          550   TCSO=EMSO*24.49
  S.0022                GO TO 770
  S.0023          660   TCSO=60.0+(EMSO-2.450)*21.74
  S.0024          770   IF(EMFI-2.450)880,880,990
  S.0025          880   TCFI=EMFI*24.49
  S.0026                GO TO 123
  S.0027          990   TCFI=60.0+(EMFI-2.450)*21.74
  S.0028          123   IF(EMFO-2.450)124,124,125
  S.0029          124   TCFO=EMFO*24.49
  S.0030                GO TO 126
  S.0031          125   TCFO=60.0+(EMFO-2.450)*21.74
  S.0032          126   TFSI=(TCSI-2.*(TCSI-TCR)/(100.-TCR))*1.8+32.0
  S.0033                TFSO=(TCSO-2.*(TCSO-TCR)/(100.-TCR))*1.8+32.0
  S.0034                TFFI=(TCFI-2.*(TCFI-TCR)/(100.-TCR))*1.8+32.0
  S.0035                TFFO=(TCFO-2.*(TCFO-TCR)/(100.-TCR))*1.8+32.0
  S.0036                X1=374.11-TCSI
  S.0037                AS1=2.303*X1/(TCSI+273.16)*(A1+A2*X1+C*X1**3)/(1.+D*X1)
  S.0038                X2=374.11-TCSO
  S.0039                AS2=2.303*X2/(TCSO+273.16)*(A1+A2*X2+C*X2**3)/(1.+D*X2)
  S.0040                Y1=374.11-TCFI
  S.0041                AF1=2.303*Y1/(TCFI+273.16)*(A1+A2*Y1+C*Y1**3)/(1.+D*Y1)
  S.0042                Y2=374.11-TCFO
  S.0043                AF2=2.303*Y2/(TCFO+273.16)*(A1+A2*Y2+C*Y2**3)/(1.+D*Y2)
  S.0044                PS1=6528.5*EXP(-AS1)
  S.0045                PS2=6528.5*EXP(-AS2)
```

```
      PF1=6528.5*EXP(-AF1)
      PF2=6528.5*EXP(-AF2)
      PE1=PS1*0.96
      PE2=PS2*0.96
      DP1=PE1-PF2
      DP2=PE2-PF1
      PSM(J)=(PE1+PE2)/2.
      PFM(J)=(PF1+PF2)/2.
      DPM(J)=(DP1-DP2)/(ALOG(DP1)-ALOG(DP2))
      WH(J)=W*60./(454.*TIME*AR)
      WH1(J)=W*60./(454.*TIME)
      WTC(J)=WH(J)/DPM(J)
      DT1=TFSI-TFFO
      DT2=TFSO-TFFI
      DTM(J)=(DT1-DT2)/(ALOG(DT1)-ALOG(DT2))
      TSM(J)=(TFSI+TFSO)/2.
      TFM(J)=(TFFI+TFFO)/2.
      TM(J)=(TSM(J)+TFM(J))/2.
      TM1(J)=TM(J)+460.
      H1=1126.1+0.396*(TSM(J)-150.)
      H2=TSM(J)-32.
      DHV(J)=H1-H2
      P1(J)=PP/0.4912
      QV=WH(J)*H1
      WF(J)=FF*60./(454.*AR)
      WF1(J)=FF*60./(454.*0.0052)
      HSI=TFSI-32.
      HSO=TFSO-32.
      QT=WF(J)*HSI-(WF(J)-WH(J))*HSO
      DQ=QT-QV
      HTC(J)=DQ/DTM(J)
      WRITE(3,321)P1(J),WF1(J),TFSI,TFSO,TFFI,TFFO,PE1,PE2,PF1,PF2
      WRITE(3,323)WH1(J),DQ,WTC(J),HTC(J)
      J=J+1
      IF(N)412,412,110
  412 STOP
  300 FORMAT(7F10.4,I2)
  401 FORMAT(4F10.4)
  321 FORMAT(/10F10.3)
  323 FORMAT(/4F10.3)
      END
```

APPENDIX IV

LEAST-SQUARES APPROXIMATING TECHNIQUE

The type of equation used for analyzing the data and results is

$$Y = \sum_{j=1}^{n} B_j X_j$$

Where (X_j), $j = 1, 2, 3, \ldots\ldots, n$ are a sequence of parameters computed from independent variables, B_j's are least-squares constants, and Y is the dependent variable.

The program used in computation of the least-squares constants is given in this appendix.

```
LEVEL: 1JUL66                                    IBM OS/360 BASIC FORTRAN IV (E) COMPILATION

                C      LEAST SQUARE PROGRAM
  S.0001               DIMENSION B(20),X(200,10),XT(10,200),XI(20,20),F(200),XTX(20,20)
  S.0002               DIMENSION XTF(20),A(20,20),Y(20),P(200)
  S.0003               DIMENSION WTC(200),TM(200),WF(200),DHV(200),WH1(200),P1(200)
  S.0004               DIMENSION TSM(200),TFM(200),DTM(200),HTC(200),DPM(200)
  S.0005               DIMENSION PSM(200),PFM(200),WF1(200),TM1(200),WH(200),PBM(200)
  S.0006               J=1
  S.0007               A1=3.2438
  S.0008               A2=5.8683E-3
  S.0009               C=1.1702E-8
  S.0010               D=2.1878E-3
  S.0011               AR=0.288
  S.0012           110 READ(1,300)EMSI,EMSO,EMFI,EMFO,TCR,TIME,W,N
  S.0013               READ(1,401)FF,PP
  S.0014               EMSI=EMSI+TCR/24.49
  S.0015               EMSO=EMSO+TCR/24.49
  S.0016               EMFI=EMFI+TCR/24.49
  S.0017               EMFO=EMFO+TCR/24.49
  S.0018               IF(EMSI-2.450)220,220,330
  S.0019           220 TCSI=EMSI*24.49
  S.0020               GO TO 440
  S.0021           330 TCSI=60.0+(EMSI-2.450)*21.74
  S.0022           440 IF(EMSO-2.450)550,550,660
  S.0023           550 TCSO=EMSO*24.49
  S.0024               GO TO 770
  S.0025           660 TCSO=60.0+(EMSO-2.450)*21.74
  S.0026           770 IF(EMFI-2.450)880,880,990
  S.0027           880 TCFI=EMFI*24.49
  S.0028               GO TO 123
  S.0029           990 TCFI=60.0+(EMFI-2.450)*21.74
  S.0030           123 IF(EMFO-2.450)124,124,125
  S.0031           124 TCFO=EMFO*24.49
  S.0032               GO TO 126
  S.0033           125 TCFO=60.0+(EMFO-2.450)*21.74
  S.0034           126 TFSI=(TCSI-2.*(TCSI-TCR)/(100.-TCR))*1.8+32.0
  S.0035               TFSO=(TCSO-2.*(TCSO-TCR)/(100.-TCR))*1.8+32.0
  S.0036               TFFI=(TCFI-2.*(TCFI-TCR)/(100.-TCR))*1.8+32.0
  S.0037               TFFO=(TCFO-2.*(TCFO-TCR)/(100.-TCR))*1.8+32.0
  S.0038               X1=374.11-TCSI
  S.0039               AS1=2.303*X1/(TCSI+273.16)*(A1+A2*X1+C*X1**3)/(1.+D*X1)
  S.0040               X2=374.11-TCSO
  S.0041               AS2=2.303*X2/(TCSO+273.16)*(A1+A2*X2+C*X2**3)/(1.+D*X2)
  S.0042               Y1=374.11-TCFI
  S.0043               AF1=2.303*Y1/(TCFI+273.16)*(A1+A2*Y1+C*Y1**3)/(1.+D*Y1)
  S.0044               Y2=374.11-TCFO
  S.0045               AF2=2.303*Y2/(TCFO+273.16)*(A1+A2*Y2+C*Y2**3)/(1.+D*Y2)
```

```
      PS1=6528.5*EXP(-AS1)
      PS2=6528.5*EXP(-AS2)
      PF1=6528.5*EXP(-AF1)
      PF2=6528.5*EXP(-AF2)
      PE1=PS1*0.96
      PE2=PS2*0.96
      DP1=PE1-PF2
      DP2=PE2-PF1
      PSM(J)=(PE1+PF2)/2.
      PFM(J)=(PF1+PF2)/2.
      DPM(J)=(DP1-DP2)/(ALOG(DP1)-ALOG(DP2))
      WH(J)=W*60./(454.*TIME*AR)
      WH1(J)=W*60./(454.*TIME)
      WTC(J)=WH(J)/DPM(J)
      DT1=TFSI-TFFO
      DT2=TFSO-TFFI
      DTM(J)=(DT1-DT2)/(ALOG(DT1)-ALOG(DT2))
      TSM(J)=(TFSI+TFSO)/2.
      TFM(J)=(TFFI+TFFO)/2.
      TM(J)=(TSM(J)+TFM(J))/2.
      TM1(J)=TM(J)+460.
      H1=1126.1+0.396*(TSM(J)-150.)
      H2=TSM(J)-32.
      DHV(J)=H1-H2
      P1(J)=PP/0.4912
      PBS1=P1(J)-PE1
      PBS2=P1(J)-PE2
      PBF1=P1(J)-PF1
      PBF2=P1(J)-PF2
      PBSM=(PBS1+PBS2)/2.
      PBFM=(PBF1+PBF2)/2.
      PBM(J)=(PBSM-PBFM)/(ALOG(PBSM)-ALOG(PBFM))
      QV=WH(J)*H1
      WF(J)=FF*60./(454.*AR)
      WF1(J)=FF*60./(454.*0.0052)
      HSI=TFSI-32.
      HSO=TFSO-32.
      QT=WF(J)*HSI-(WF(J)-WH(J))*HSO
      DQ=QT-QV
      HTC(J)=DQ/DTM(J)
      J=J+1
      IF(N)777,777,110
  300 FORMAT(7F10.4,I2)
  401 FORMAT(2F10.4)
C     FUNCTIONAL APPROXIMATION - LEAST SQUARE TECHFQUE
C     F(I)=P(X(I))    I=1,2,3,.....,N       N=NUMBER OF POINTS(OR DATA)
C     FORM OF APPROXIMATE POLYNOMIAL IS
```

```
C     P(X)=B(1)+B(2)*X+B(3)*X**2+....+B(M)*X**(M-1)+B(M+1)*X**M
C     M=DEGREE OF POLYNOMIAL WANTED
C     MATRIX NOTATION : XA=F
C     MP=NUMBER OF PROBLEM TO BE SOLVED
  777 WRITE(3,101)
      READ(1,100)MP
      N=J-1
      DO 99 MM=1,MP
      WRITE(3,103)MM
C     SET UP X MATRIX
      DO 555 I=1,N
      AAA=DPM(I)*DHV(I)/DTM(I)
      BBB=P1(I)/TM1(I)
      CCC=(DTM(I)-2.5)/TM1(I)
      DDD=WF1(I)**0.5/WH(I)
      EEE=1./WF1(I)**0.3
      FFF=P1(I)**2./((2.*P1(I)+PFM(I)+PSM(I))*TM1(I)**0.5)
      GGG=1./WH(I)
      HHH=PBM(I)/P1(I)
      SSS=1./WF1(I)
      GO TO (501,502,503,504,505,506,507,508,509,510,511,512,513,514,
     1515,516,517,518,519,520),MM
  501 F(I)=1./WTC(I)
      X(I,1)=1.
      X(I,2)=BBB
      X(I,3)=DTM(I)-1.4
      MJ=3
      GO TO 555
  502 F(I)=1./WTC(I)
      X(I,1)=EEE*AAA
      X(I,2)=EEE*BBB
      X(I,3)=EEE
      MJ=3
      GO TO 555
  503 F(I)=1./WTC(I)
      X(I,1)=BBB
      X(I,2)=DTM(I)-1.4
      MJ=2
      GO TO 555
  504 F(I)=1./WTC(I)
      X(I,1)=1.
      X(I,2)=BBB
      X(I,3)=EEE
      MJ=3
      GO TO 555
  505 F(I)=1./WTC(I)
      X(I,1)=AAA
```

```
      X(I,2)=FFF
      X(I,3)=EEE
      MJ=3
      GO TO 555
  506 F(I)=1./WTC(I)
      X(I,1)=FFF
      X(I,2)=EEE
      MJ=2
      GO TO 555
  507 F(I)=1./WTC(I)
      X(I,1)=EEE*AAA
      X(I,2)=EEE*FFF
      X(I,3)=(DTM(I)-1.4)*HHH
      MJ=3
      GO TO 555
  508 F(I)=1./WTC(I)
      X(I,1)=(DTM(I)-1.4)*HHH/WF1(I)**0.3
      X(I,2)=BBB
      X(I,3)=AAA
      MJ=3
      GO TO 555
  509 F(I)=1./WTC(I)
      X(I,1)=EEE*AAA
      X(I,2)=EEE*FFF
      X(I,3)=(DTM(I)-1.4)*HHH
      X(I,4)=EEF
      MJ=4
      GO TO 555
  510 F(I)=1./WTC(I)
      X(I,1)=HHH
      X(I,2)=FFF
      X(I,3)=BBB
      MJ=3
      GO TO 555
  511 F(I)=1./WTC(I)
      X(I,1)=DTM(I)-1.4
      X(I,2)=WF1(I)
      MJ=2
      GO TO 555
  512 F(I)=1./WTC(I)
      X(I,1)=AAA
      X(I,2)=HHH
      X(I,3)=1.
      MJ=3
      GO TO 555
  513 F(I)=1./WTC(I)
      X(I,1)=AAA
```

```
      X(I,2)=DTM(I)-1.4
      X(I,3)=EEE
      MJ=3
      GO TO 555
  514 F(I)=1./WTC(I)
      X(I,1)=1.
      X(I,2)=HHH/TM1(I)**0.5
      X(I,3)=EEE
      X(I,4)=DTM(I)-1.4
      MJ=4
      GO TO 555
  515 F(I)=1./WTC(I)
      X(I,1)=1.
      X(I,2)=(DTM(I)-1.4)*P1(I)
      X(I,3)=EEE
      MJ=3
      GO TO 555
  516 F(I)=1./WTC(I)
      X(I,1)=1.
      X(I,2)=DTM(I)-1.4
      X(I,3)=WF1(I)
      X(I,4)=HHH
      MJ=4
      GO TO 555
  517 F(I)=1./WTC(I)
      X(I,1)=1.
      X(I,2)=PBM(I)
      MJ=2
      GO TO 555
  518 F(I)=1./WTC(I)
      X(I,1)=1.
      X(I,2)=(DTM(I)-1.4)*PBM(I)
      MJ=2
      GO TO 555
  519 F(I)=1./WTC(I)
      X(I,1)=EEE
      X(I,2)=(DTM(I)-1.4)*HHH
      MJ=2
      GO TO 555
  520 F(I)=1./WTC(I)
      X(I,1)=WF1(I)
      X(I,2)=(DTM(I)-1.4)*HHH
      MJ=2
      GO TO 555
  555 CONTINUE
C     TRANSPOSE X MTARIX : XT
      DO 10 I=1,MJ
```

```
      DO 10 J=1,N
   10 XT(I,J)=X(J,I)
C     FIND PRODUCT OF XT*X : XTX
      DO 16 I=1,MJ
      DO 16 J=1,MJ
      SUM=0.
      DO 15 K=1,N
   15 SUM=SUM+XT(I,K)*X(K,J)
   16 XTX(I,J)=SUM
C     FIND PRODUCT OF XT*F : XTF
      DO 21 I=1,MJ
      SUM=0.
      DO 20 J=1,N
   20 SUM=SUM+XT(I,J)*F(J)
   21 XTF(I)=SUM
C     FIND INVERSEOF XTX : XI BY GAUSSIAN ELIMINATION WITH PIVOTING
C     SET UP AUGMENTED MATRIX OF XTX, AND CHANGE THE NAME AS A
      MJ1=MJ+1
      MJ2=2*MJ
      DO 30 I=1,MJ
      DO 25 J=1,MJ
   25 A(I,J)=XTX(I,J)
      DO 30 K=MJ1,MJ2
      II=K-MJ
      IF(II-I)29,28,29
   28 A(I,K)=1.
      GO TO 30
   29 A(I,K)=0.
   30 CONTINUE
      SSSS=1.
      MARK=0.
      NMI=MJ-1
      NN=2*MJ
      NPLSY=NN
C     PICK UP PIVOT
      I=0
   32 I=I+1
      MAX=I
      AMAX=ABS(A(I,I))
      K=I
   31 K=K+1
      IF(AMAX-ABS(A(K,I)))35,40,40
   35 MAX=K
      AMAX=ABS(A(K,I))
   40 IF(MJ-K)31,45,31
   45 IF(I-MAX)50,61,50
C     ROW INTERCHANGE
```

```
   50 L=I-1
   51 L=L+1
      TEMP=A(I,L)
      A(I,L)=A(MAX,L)
      A(MAX,L)=TEMP
      IF(NPLSY-L)51,60,51
   60 SSSS=-SSSS
   61 J=I
   62 J=J+1
      IF(A(J,I))63,65,63
   63 CONST=-A(J,I)/A(I,I)
      L=I-1
   64 L=L+1
      A(J,L)=A(J,L)+A(I,L)*CONST
      IF(L-NPLSY)64,65,64
   65 IF(J-MJ)62,66,62
   66 IF(I-NMI)32,67,32
C     COMPUTE DETERMINANT(A)
   67 TEMP=1.
      I=0.
   68 I=I+1
      IF(A(I,I))69,71,69
   69 TEMP=TEMP*A(I,I)
      IF(I-MJ)68,70,68
   70 DET=SSSS*TEMP
      GO TO 72
   71 MARK=1
   72 IF(MARK-1)73,999,73
   73 I=MJ
   83 I=I+1
C     BACK SUBSTITUTION
      K=MJ
   78 Y(K)=A(K,I)
      IF(K-MJ)74,76,74
   74 J=K
   75 J=J+1
      Y(K)=Y(K)-A(K,J)*Y(J)
      IF(J-MJ)75,76,75
   76 Y(K)=Y(K)/A(K,K)
      IF(K-1)77,79,77
   77 K=K-1
      GO TO 78
   79 L=0
   80 L=L+1
      A(L,I)=Y(L)
      IF(L-MJ)80,81,80
   81 IMJ=I-MJ
```

```
      DO 82 KK=1,MJ
   82 XI(KK,IMJ)=Y(KK)
      IF(I-NPLSY)83,84,83
C     FIND B(I) ,I=1,2,3,.....,M,M+1
C     B=XI*XTF
   84 DO 87 I=1,MJ
      SUM=0.
      DO 86 J=1,MJ
   86 SUM=SUM+XI(I,J)*XTF(J)
   87 B(I)=SUM
C     FIND STANDARD DEVIATION AND ERROR
      FF=0.0
      DO 88 I=1,N
   88 FF=FF+F(I)*F(I)
      RDTB=0.0
      DO 89 I=1,MJ
   89 RDTB=RDTB+B(I)*XTF(I)
      SSE=FF-RDTB
      EDF=N-MJ
      SSEM=SSE/EDF
      ESTDV=SQRT(ABS(SSEM))
      WRITE(3,106)
      WRITE(3,105)
      DO 90 I=1,MJ
      BSTDV=SQRT(ABS(XI(I,I)*SSEM))
      WRITE(3,105)
   90 WRITE(3,107)I,B(I),BSTDV
      WRITE(3,105)
      WRITE(3,108)ESTDV
      WRITE(3,105)
      WRITE(3,109)
      DO 92 I=1,N
      SUM=0.
      DO 91 K=1,MJ
   91 SUM=SUM+B(K)*X(I,K)
      P(I)=SUM
   92 WRITE(3,111)I,F(I),P(I),WTC(I),HTC(I)
      GO TO 99
  999 WRITE(3,102)
   99 CONTINUE
  100 FORMAT(7I10)
  101 FORMAT(1H1)
  102 FORMAT(5X,'SINGULAR')
  103 FORMAT(/////5X,'PROBLEM',I3//)
  105 FORMAT(/)
  106 FORMAT(4X,'BETA',7X,'ESTIMATE',5X,'STANDARD DEVIATION')
  107 FORMAT(I7,6X,E11.4,7X,E11.4)
  108 FORMAT(3X,'ERROR',23X,E11.4)
  109 FORMAT(7X,'I',11X,'F(I)',11X,'P(I)')
      STOP
  111 FORMAT(I8,6E18.8)
      END
```

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