

DISTILLATION OF AN ETHANOL-WATER BINARY
MIXTURE IN A HORIZONTAL DISTILLATION
TUBE UTILIZING VAPOR RECOMPRESSION

by

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B.S., Kansas State University, 1980

A MASTER'S THESIS

submitted in partial fulfillment of the
requirement for the degree

MASTER OF SCIENCE

Department of Mechanical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1982

Approved by


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NOMENCLATURE

Symbol	Description	Units
C_p	Specific heat capacitance	BTU/lb-mole °F
k	Ratio of specific heats	-----
P	Pressure	lb _f /in ²
P°	Vapor pressure, (equilibrium pressure)	lb _f /in ²
R	Universal gas constant	BTU/lb-mole °R
T	Temperature	°F or °R
v	Specific volume	ft ³ /lb _m
W	Work	BTU/hr
X	Mole fraction in liquid form	-----
Y	Mole fraction in vapor form	-----

SUBSCRIPTS

A	Component A	-----
B	Component B	-----
FS	Feed stock	-----
T	Total	-----
$1,2,\dots,13$	Thermocouple and temperature locations.	-----

Note: Variables used in the computer model are listed in Appendix A.

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CHAPTER I

INTRODUCTION

Distillation is a widely used method of separating the liquid constituents of a liquid solution by vaporizing the solution and condensing the components separately. The Chinese are reported to have distilled a beverage from rice beer as early as 800 B.C. Aristotle was aware of purifying sea water by evaporation in the 4th century B.C. Arabs produced a distilled beverage from wine and the Alexandrians prepared oil of turpentine by distilling pine resin, (1).

By the early 1800's, the French and British had developed bubble plate towers for large scale distillation of alcoholic beverages. These bubble plate towers are similar to those used in present day distillation operations, Figure 1. Packed columns are also common in distillation columns as shown in Figure 2.

During the distillation process, the liquid solution is fed into the column. It is allowed to flow down the packing or to enter a bubble tray level. The liquid is vaporized by hot vapors rising through the column. Liquid that does not vaporize, flows to the bottom of the column where it is heated and vaporized by the reboiler. As the vapors rise they are condensed and revaporized at various levels in the packing or bubble tray levels. This is brought about by the temperature gradient that exists in the column. As the vapors rise the temperature drops. The less volatile component will begin to condense out of the solution resulting in an increase in the richness of the vapors, with the more volatile component. The descending liquid will decrease in concentration of the more volatile component as it flows to the bottom.

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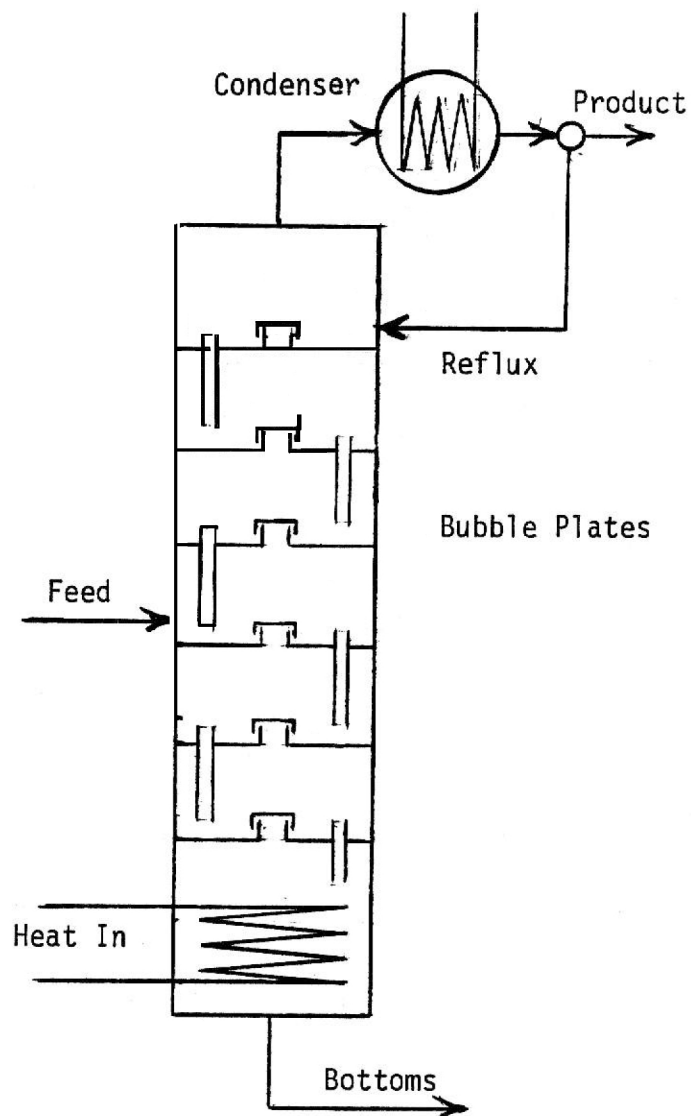


Figure 1. Distillation column using bubble plates.

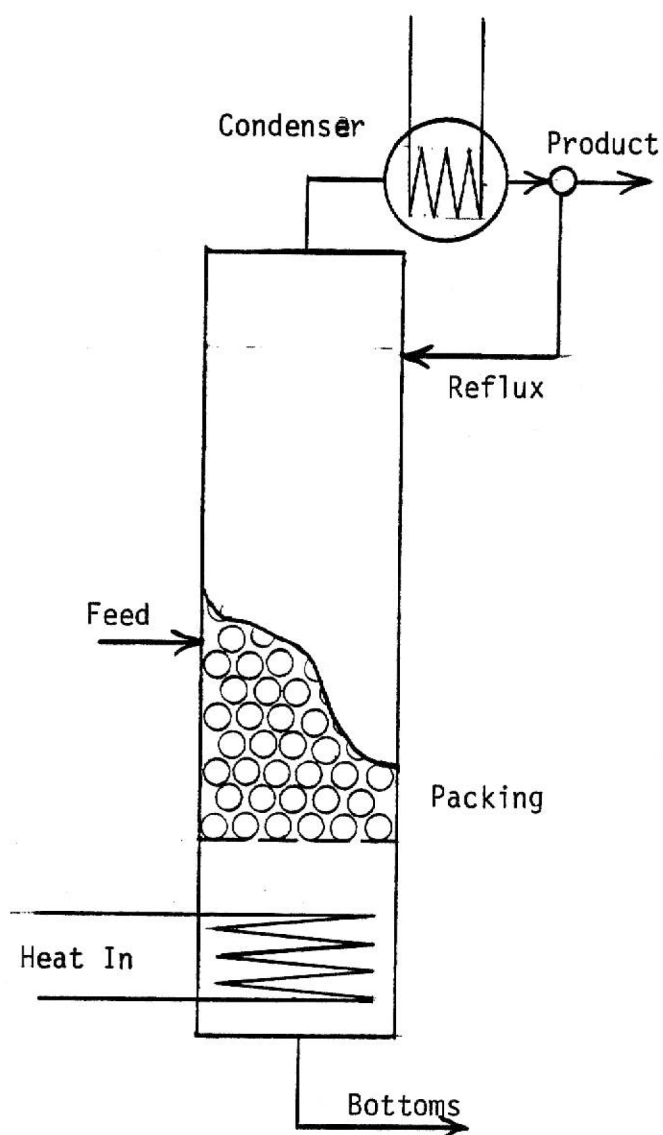


Figure 2. Distillation column using packed column.

The concentration of the exiting vapor is increased further by reintroducing part of the vapors into the column after they have condensed to a liquid. This process is known as reflux. The proportion refluxed to the column is given by the "Reflux Ratio" which is the ratio of the number of moles liquid returned to the column to the number of moles removed as product.

Reflux increases the concentration due to the effects of phase equilibrium of a solution. At any given concentration and corresponding boiling temperature and pressure the liquid and vapor achieve an equilibrium condition. The mole fraction of the more volatile component will be greater in vapor form than in the liquid. Thus, when the liquid is refluxed into the column, vapor that evaporates from the liquid will have a higher mole fraction of the more volatile component than the liquid refluxed into the column.

ENERGY REQUIREMENTS OF DISTILLATION

The minimum amount of energy required for separation of a mixture is equivalent to the change in entropy that occurs at a given temperature when the components are mixed. In reality the energy required for distillation far exceeds this minimum amount due to inefficiencies in the distillation process and heat losses, (2). In order to determine how efficient a particular distillation process is, it is necessary to know what the minimum amount of work required to perform the distillation is.

One such way is to consider the separation of Component A from an infinite liquid feedstock (3). Component A is vaporized and separated from the infinite feedstock by passage through a semi-permeable membrane which

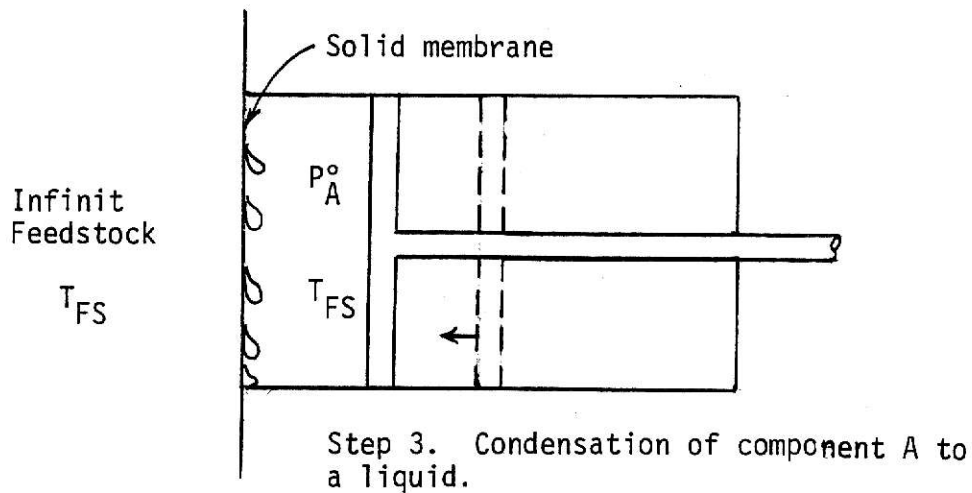
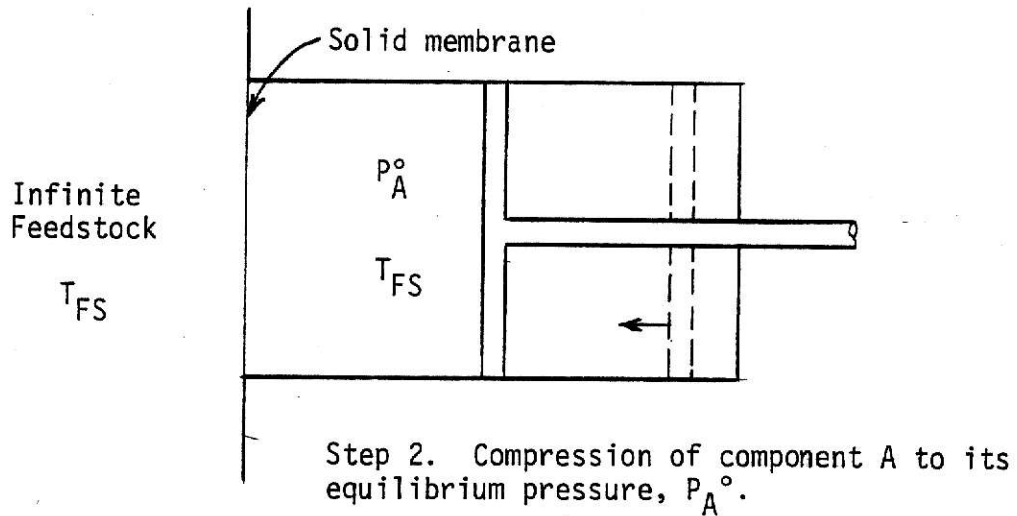
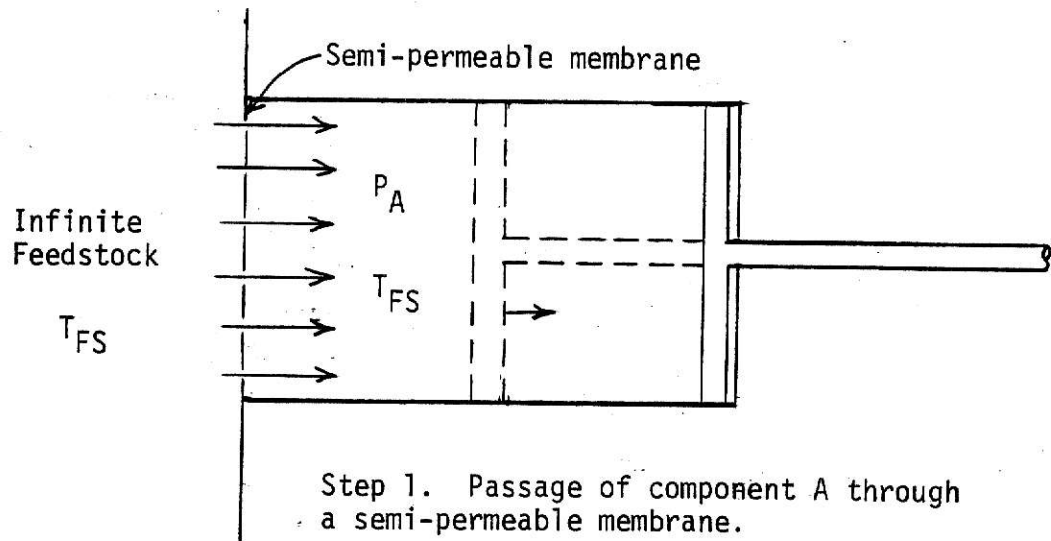


Figure 3. Ideal separation process.

allows for the passage of Component A only. This action takes place at the feedstock temperature, T_{FS} , Component A's partial pressure in the feedstock, P_A , and its corresponding specific volume, v_A . By reducing the equation of the First Law of Thermodynamics, Equation 1 is formed. This equation shows the work required for separation of Component A through the membrane.

$$W_{SEPARATION} = P_A(v_{A(vapor)} - v_{A(liquid)}) = P_A(v_{A(vapor)}) \quad (1)$$

Since the specific volume of liquid, $v_{A(liquid)}$, is small compared to the specific volume of vapor, $v_{A(vapor)}$, the specific volume of liquid is ignored.

The vapor of Component A is then compressed to its equilibrium, (vapor), pressure, P_A° , as a pure substance. This compression is considered to be reversible and isothermal. Equation 2 gives the work required for this compression.

$$W_{COMPRESSION} = -RT \ln \frac{P_A^\circ}{P_A} \quad (2)$$

Finally the vapors are condensed through a membrane at the feedstock temperature, T_{FS} . The work required for this process is given by Equation 3. These processes are considered to be reversible and isothermal.

$$\begin{aligned} W &= -P_A^\circ(v_{A^\circ(vapor)} - v_{A^\circ(liquid)}) \\ &= -P_A^\circ v_{A^\circ(vapor)} \end{aligned} \quad (3)$$

By utilizing ideal gas laws, it can be shown that

$$P_A v_A = P_A^\circ v_{A^\circ} = RT \quad (4)$$

Then substituting Equation 4 into Equations 1 and 2, and summing equations 1,2 and 3 will result in Equation 2 which is the minimum amount of work required for separation.

Further reduction of Equation 2 can be made by applying Raoult's law of an ideal mixture. This is given by Equation 5 where X_A is the mole fraction of Component A in the liquid feedstock.

$$X_A = \frac{P_A^\circ}{P_A} \quad (5)$$

By substituting Equation 5 into 2, the ideal work of separation required to obtain one mole of Component A is reduced to the following equation.

$$W_{\text{SEPARATION}} = -RT \ln X_A \quad (6)$$

By repeating the above procedure, the work required for separation of one mole of Component B from an infinite feedstock can be determined. This results in an equation similar to Equation 6 where the mole fraction of Component B is X_B . A weighted average can then be applied to determine the amount of work required for separating one mole of a solution containing Components A and B. This is expressed in Equation 7, where $X_B = 1 - X_A$, as

$$W_{\text{SEPARATION}} = -RT[X_A \ln X_A + X_B \ln X_B]. \quad (7)$$

Figure 4 plots the ideal work required to separate one mole of solution, and to achieve one mole of the desired component as a function of concentration.

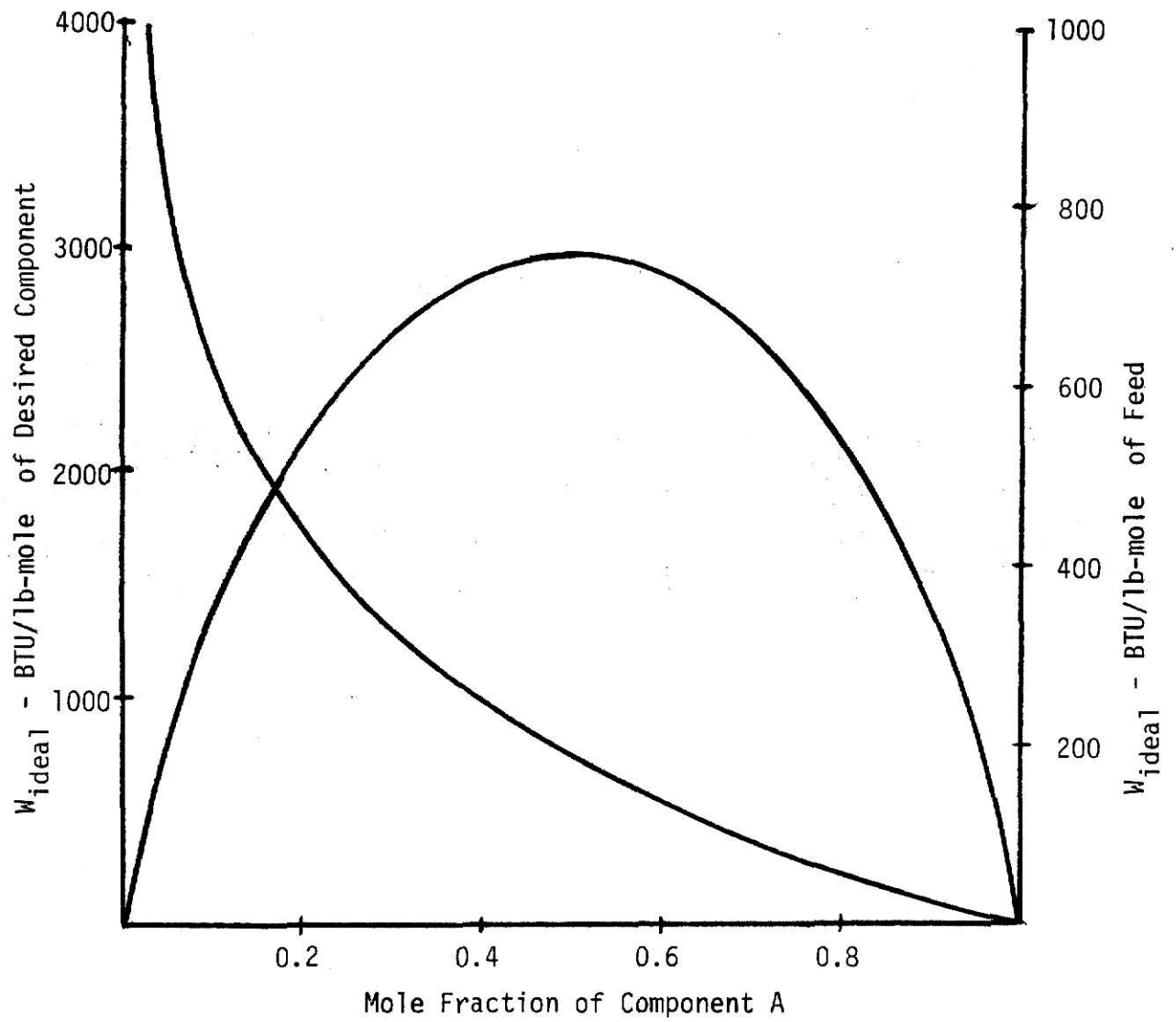


Figure 4. Graph of ideal work of separation as a function of concentration for an ideal solution.

METHODS OF ENERGY SAVINGS

The previous section discusses the amount of energy required for the separation of a binary mixture. Techniques of normal distillation far exceed the minimum work required for separation. Two methods of energy savings have been proposed that would reduce present energy consumption and approach the ideal energy requirement. The first of these is the multi-effect distillation system, Figure 5, and second is the use of vapor recompression, Figure 6.

Multi-effect distillation has been presented as an energy saving measure several times. Robinson and Gillard (4), Pratt (5), Tyreus and Luyben (6), and O'Brien (7) are some of the articles that have discussed the idea. The principle behind multi-effect distillation is to use more effectively the available energy. This is achieved by operating several columns in series at different pressures. By operating at progressively lower pressures, the condenser of a column operating at a high pressure will act as the boiler for a column operating at a lower pressure. This way, energy only has to be supplied to vaporize liquid in the first column and to maintain the different pressures required in individual columns.

An ideal vapor recompression system, Figure 6, approaches the minimum work required for separation in an ideal column as presented in Equation 7. This is achieved by compression of the exiting vapors to a higher pressure. The compression raises the temperature of the vapor and therefore increases the availability of energy in the vapor. With the compressed vapor at a higher temperature than the reboiler, heat transfer takes place. The compressed vapor is allowed to condense in the reboiler and release its latent heat of vaporization which in turn will vaporize an equivalent amount of the

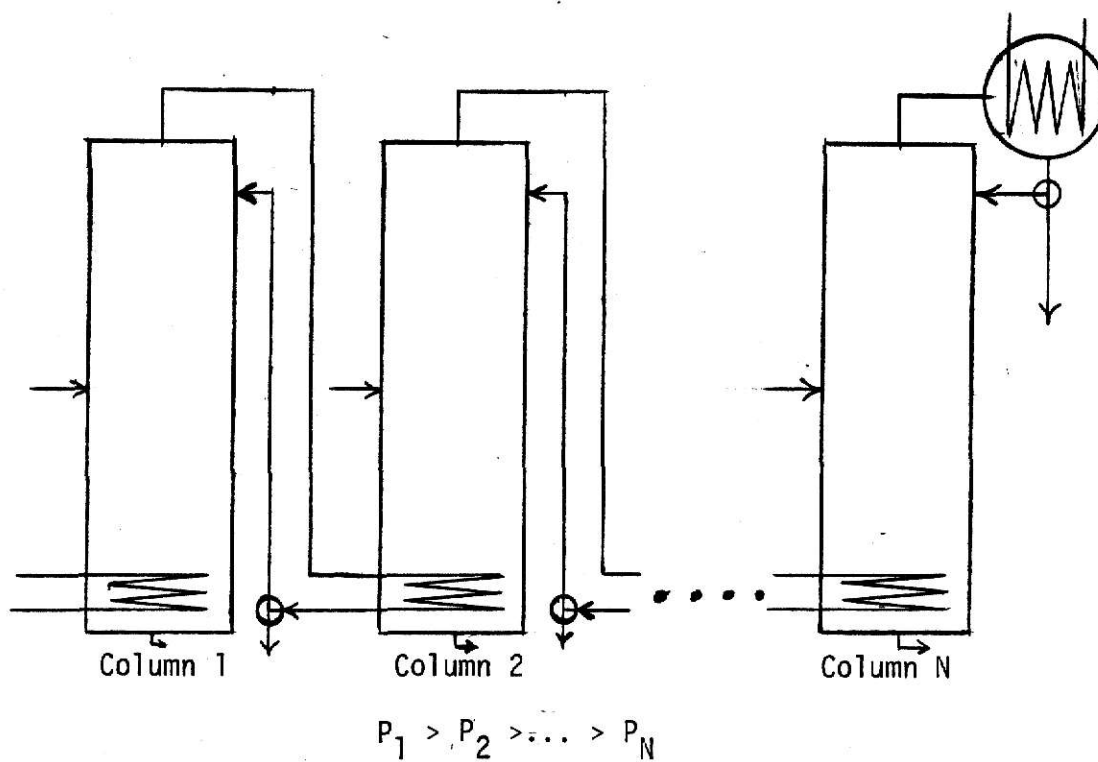


Figure 5. Schematic of multi-effect distillation.

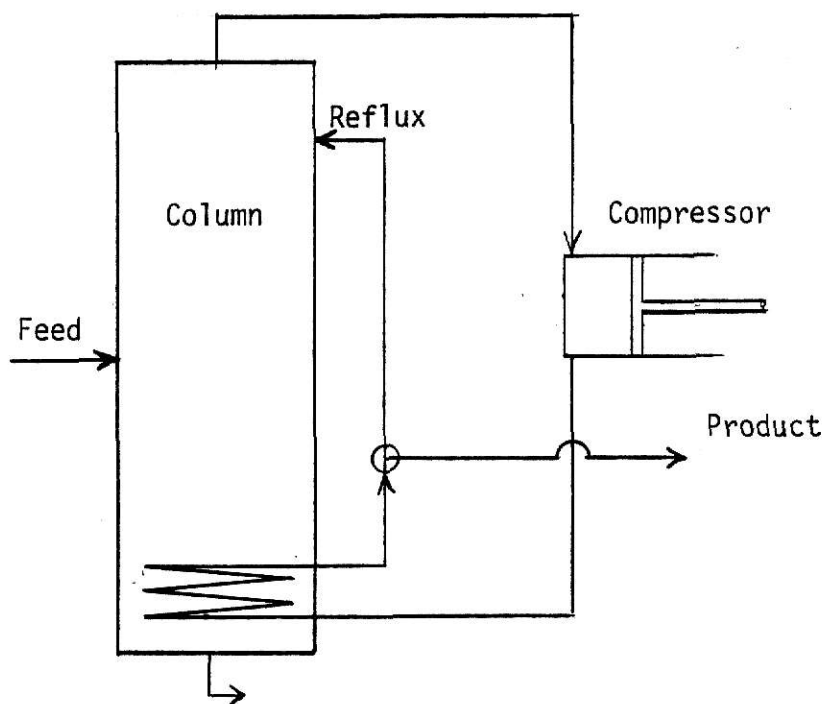


Figure 6. Schematic of vapor recompression.

liquid solution.

Tyrevs and Luyben discuss the use of a two column system to replace a single column. They present energy and economic analyses for separating a propylene-propane solution and an ethanol-water solution. The use of two columns was shown to produce an energy savings compared to a single column. A comparison with vapor recompression was also made. The vapor recompression system was determined to be more energy efficient. But because of the added capital and maintenance cost required for the compressor, the two column system obtained a slight advantage in terms of economics.

In 1923, one of the first patents which utilized vapor recompression was granted in France (8). Fowler and Jackson (9) discuss the energy requirement for distillation and the use of heat pumps and vapor recompression. A reduction of twenty-five to seventy-five percent of the overall energy requirement is possible by utilizing vapor recompression (10).

In 1951 and 1961, Freshwater (2,11) discussed the thermal economy of using multiple effect columns and vapor recompression in distillation. Fitzmorris and Mah (12) performed an availability analysis on a conventional distillation column and compared it with vapor-recompression and another scheme called Secondary Reflux and Vaporization (SRV). The SRV scheme used a system similar to a multi-effect distillation system and added vapor recompression.

Use of an external heat pump cycle between the condenser and boiler was discussed by Null (13). The heat pump cycle was compared to a conventional distillation system and to a system utilizing vapor recompression.

Danzinger and Baumer (8) discussed the use of vapor recompression in a pilot plant built by the Sulzer Brothers Limited of Switzerland around 1977. The column was 0.25 meter in diameter and had a packed height of 12 meters. A two stage turbo-blower was used for the compression of the vapors. Results from their initial experimentation show much promise for the reduction of energy required for distillation.

The most common reason for not utilizing vapor recompression has been the economics involved. Increased capital cost of installing the compressor and additional heat exchangers, and the higher maintenance cost of the compressor have offset the energy savings. But since energy prices have soared in the past decade, vapor recompression may become an attractive energy saving alternative in distillation systems.

PROPOSED DISTILLATION SYSTEM

The previous section introduced the scheme of using vapor recompression, Figure 6, to approach the minimum work of separation, Equation 7, required to distill a solution. By compressing the overhead vapor in an adiabatic process, the temperature of the vapor is increased. Equation 8 gives the relationship for an ideal case.

$$T_2 = T_1 \left(\frac{P_2}{P_1} \right)^{\frac{k-1}{k}} \quad (8)$$

The compressed vapors, now at a higher temperature, pass through the boiler, (or reboiler), and condense releasing their latent heat of vaporization. Liquid in the boiler is then vaporized and allowed to raise through the column.

Most distillation columns in use today utilize a vertical column either containing bubble trays or some type of packing material. An alternative to this arrangement is to rotate the distillation column from a vertical axis to a horizontal axis. This horizontal column allows for installation in confined areas where height may pose a problem. Also, the horizontal distillation tube tends not to be as sensitive to flow rates as a vertical column thus allowing for variable rates of distillation using the same distillation tube. This allows for the use of alternate means of supplying work energy that may not be constant, (i.e. windmill, waterfall, etc.). Throughout this thesis the horizontal column will be referred to as a horizontal distillation tube.

The concentration of the liquid and vapor solution in the distillation tube will vary from one end to the other as compared from top to bottom of a vertical column. To achieve this variance in concentration, a series of screens are spaced along the length of the distillation tube and rotated. A liquid level is maintained along the bottom of the distillation tube. The rotating screens lift liquid into the vapor stream which is flowing through the column. Since the liquid and vapor are at different concentrations they are mixed and allowed to come to an equilibrium composition. Vapor then flows to the next screen and liquid drops back to the liquid portion of the distillation tube at a new concentration. This process continues throughout the distillation tube until the vapor is removed at the exit. The rotating screens are designed such that the liquid is separated into individual compartments thus allowing for different concentrations. This could be compared to the different bubble tray levels in a conventional

column. The concentration of the liquid is increased by refluxing part of the condensed vapors.

The proposed distillation system under study in this thesis incorporates the idea of a horizontal distillation tube utilizing vapor recompression. Figure 7 presents a schematic of this system. Vapor is drawn off a batch boiler, A, at its boiling temperature and pulled into the distillation tube, C. The separation process takes place along the length of the tube, C to E. Temperature of the tube drops as vapor exits the opposite end, E, and is compressed by the vacuum pump, F. This temperature gradient corresponds to the change in boiling temperature of the solution as its concentration is increased. Reflux of cooled liquid aids in producing this temperature gradient.

As the vapor is compressed in the pump to atmospheric pressure, an increase in temperature results. The vapor, now at a higher temperature than the boiler, passes through a heat exchanger located in the boiler, G. Condensation of the vapor takes place releasing the latent heat of vaporization present in the vapor causing liquid in the boiler to vaporize. This liquid next passes through an auxiliary heat exchanger, H, to condense any vapor that may remain and cool the liquid. All or part of the liquid is then refluxed back into the distillation tube through an expansion valve, J. Liquid is removed at a control valve if it is of sufficient concentration, but part of the liquid must be refluxed to maintain the desired concentration.

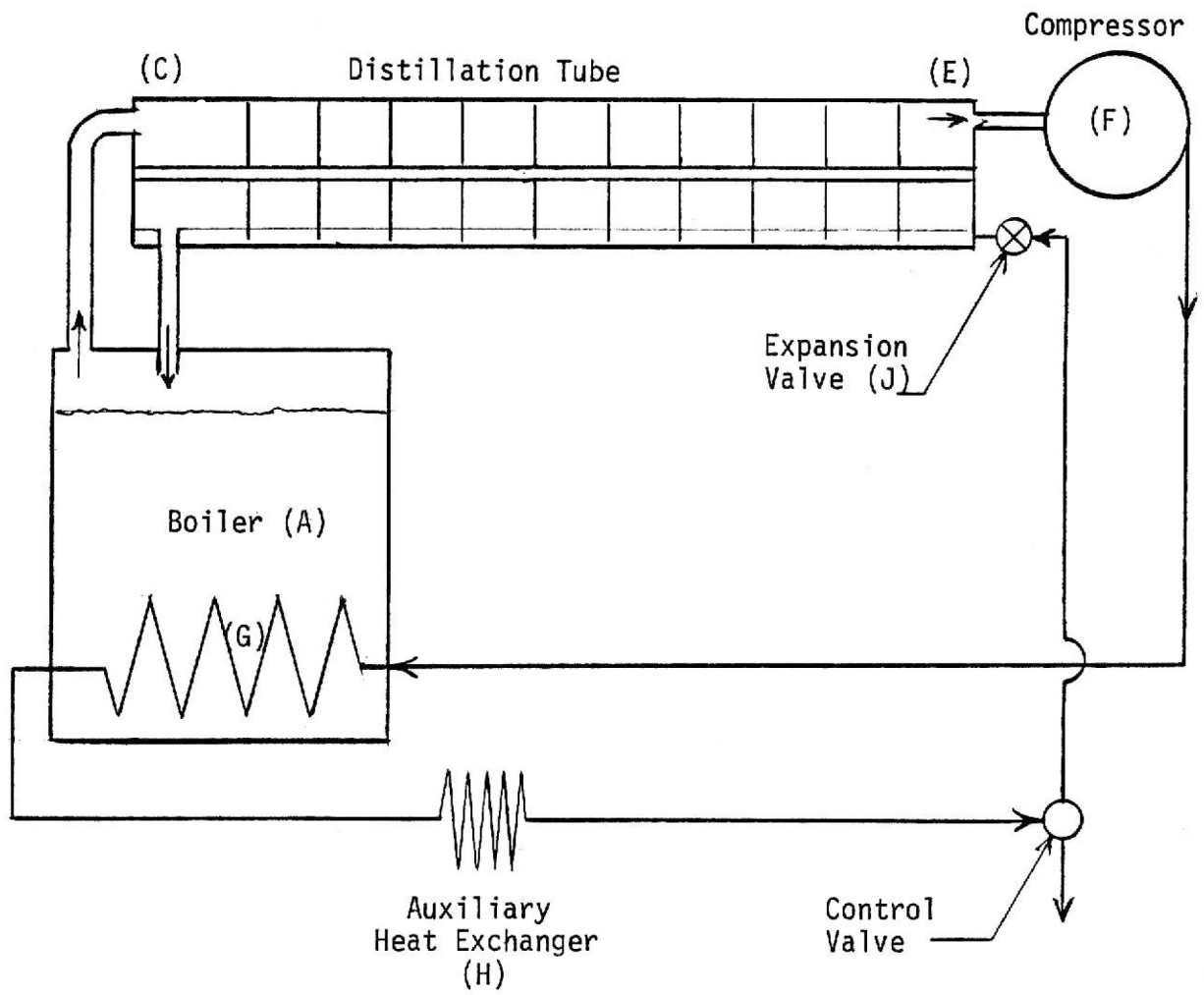


Figure 7. Schematic of proposed distillation system.

OBJECTIVE OF RESEARCH

The objective of research undertaken by the author, is to determine if the proposed distillation system is actually possible. This is achieved through two major operations. The first operation was to develop a computer program to model the physical happenings of the proposed system. The second operation was to build a small scale working model based on the proposed distillation system.

CHAPTER II

COMPUTER MODEL

The first objective of research was to evaluate the proposed distillation system by development of a computer model. This computer model consists of a main program which calls upon six different subroutines. Each subroutine models an individual component of the distillation system or provides necessary information about the system to other parts of the computer program. Included in the appendix is a listing of the computer program along with a list of variables used in the program. Figure 8 shows a sequence of the subroutines. In order to understand the distillation system, the concept of equilibrium is first introduced.

IDEAL EQUILIBRIUM

When a liquid solution is at its boiling point, the liquid that vaporizes is at a different concentration than the liquid itself. The vapor will have a higher concentration of the more volatile component in the solution. For an ideal binary mixture the concentration of the liquid and vapor can be described by Raoult's laws of equilibrium.

Raoult's laws give concentration as a function of vapor pressure of each component and the total pressure (i.e. pressure of the surroundings). Vapor pressure in turn is a function of temperature. The mole fraction of Component A in liquid phase is given as

$$x_A = \frac{P_T - P_B^{\circ}}{P_A^{\circ} - P_B^{\circ}} \quad (9)$$

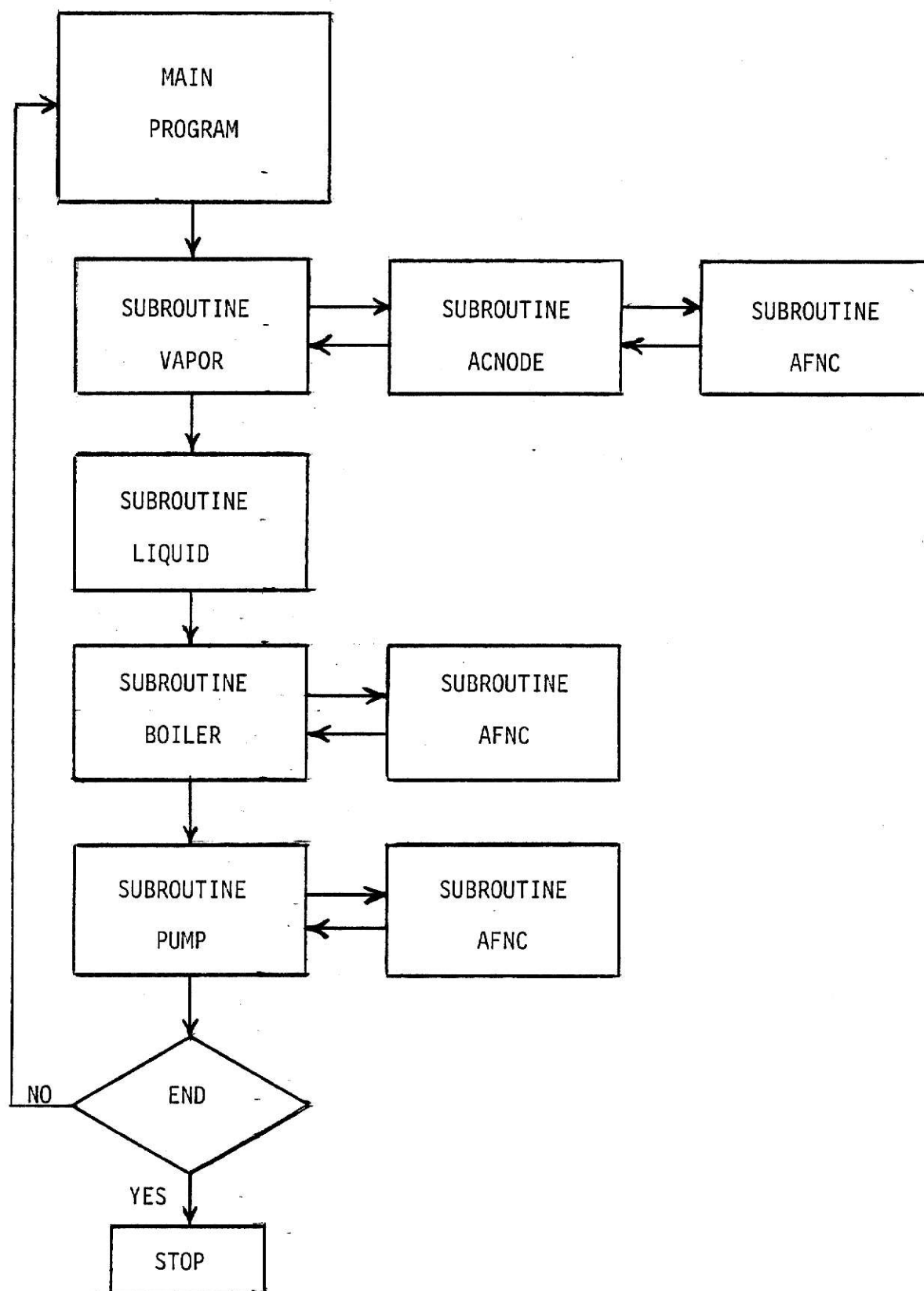


Figure 8. Block diagram of computer model.

Mole fraction of Component B in liquid phase is then

$$X_B = 1.0 - X_A \quad (10)$$

The mole fraction of Component A in vapor phase is given by

$$Y_A = X_A \left(\frac{P_A^\circ}{P_T} \right) \quad (11)$$

Mole fraction of Component B in vapor phase is then given by

$$Y_B = 1.0 - Y_A \quad (12)$$

The phase equilibrium diagram for an ethanol water solution using Raoult's Laws is shown in Figure 9. This equilibrium diagram shown is for a constant pressure, P_T , of 4 psia. An example of how to use the equilibrium diagram is as follows. A liquid solution of 0.5 mole fraction ethanol will boil at 133°F, point A. The vapor that is released from the liquid will be at a concentration of .70 mole fraction ethanol, point B, at a constant temperature.

OPERATING PRINCIPLE OF THE DISTILLATION SYSTEM

With the brief introduction to equilibrium now presented it is possible to describe the operating principle of the distillation system, Figure 7. In Chapter I a brief overview of the distillation system was made. The heart of the system lies in the horizontal distillation tube where the process of enriching the solution takes place. Located inside the distillation tube is a series of rotating screens which are designed to lift liquid from the liquid portion of the tube, bottom, into the vapor portion as shown in Figure 10. These screens also restrict the flow of liquid thus producing many small reservoirs of liquid at increasing concentrations

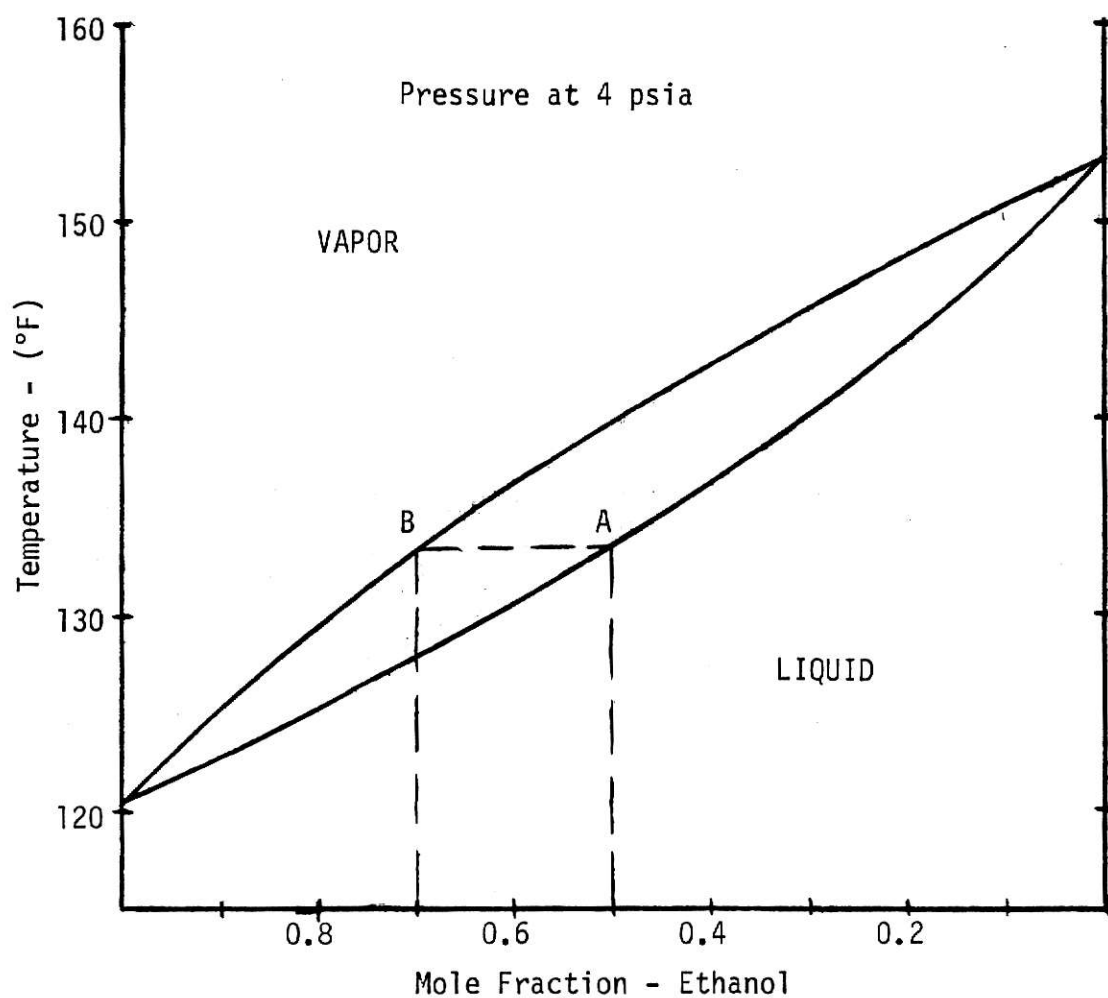


Figure 9. Ideal phase equilibrium diagram for ethanol-water mixture.

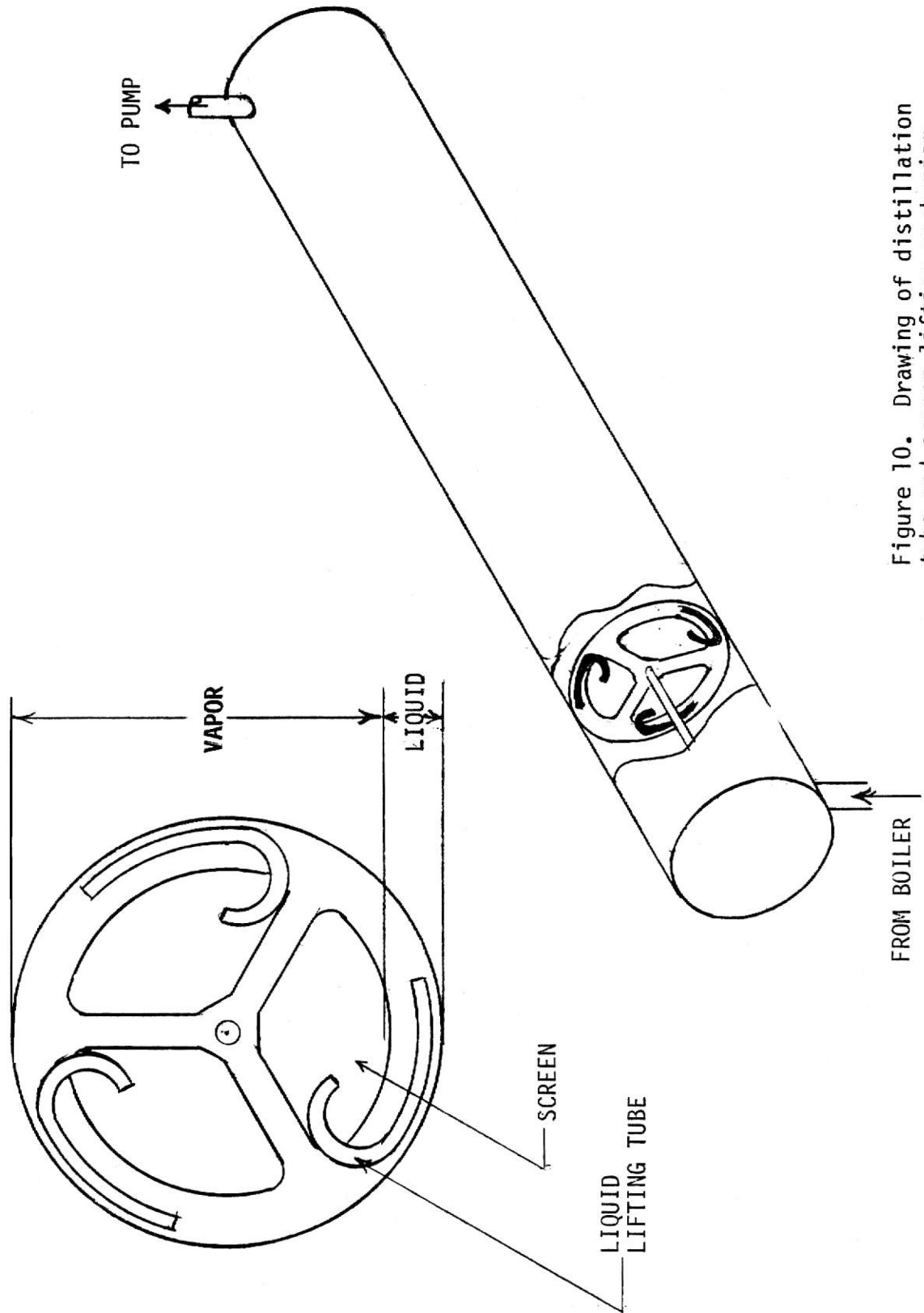


Figure 10. Drawing of distillation tube and screen lifting mechanism.

through the length of the tube. Vapor flows from the boiler through the tube and exits to the pump. As the vapor flows through, liquid is mixed with the vapor as it passes through the screens. Since the vapor and liquid are at different concentrations and temperature, the mixing process creates a new equilibrium concentration and temperature for the vapor and liquid. The vapor that flows on after new equilibrium is achieved, is at a higher concentration and slightly lower temperature. The liquid that falls back to the liquid portion of the distillation tube is at a slightly lower concentration and higher temperature than before mixing.

This process of mixing vapor with liquid takes place throughout the distillation tube. As the vapor flows through the tube its concentration is increased. The liquid concentration also increases along the length of the tube until a steady state condition is achieved. A concentration gradient and temperature gradient then exist through the length of the tube. The entrance from the boiler will have the lowest concentration and highest temperature. At the exit, the concentration will be at its highest and the temperature at its lowest.

In order to further enrich the solution part of the vapors exiting the distillation tube are reintroduced into the column once they are condensed to a liquid, (i.e. Reflux). This provides for a higher concentration of liquid at the exiting end of the tube. Reflux also lowers the temperature at the exiting end of the tube.

The remainder of the distillation system consists of a boiler, pump, heat exchangers, and piping between the components with valves. Located in the boiler is the raw solution that is to be distilled. Heat is furnished to the liquid in the boiler by a heat exchanger in which vapors from the distillation tube pass after they have been compressed to a higher

pressure by the pump. By compressing the vapors, an increase in temperature takes place thus creating the temperature differential necessary to condense the vapor and release their latent energy to the liquid in the boiler. A secondary heat exchanger is used to cool the liquid further. The liquid is then either removed from the system or refluxed into the distillation tube through an expansion valve.

PARAMETERS

A binary mixture of water and ethanol is considered to be the solution distilled in the computer model. The objective is to start with a solution of five mole percent ethanol and distill it to a solution of sixty-five mole percent ethanol. Operating pressures inside the distillation tube, PST, were tried at several different pressures. Initial runs were made at 3 psia and then latter changed to 4, 6 and 8 psia. The pressure on the high side of the pump, P2, was maintained at atmospheric pressure.

Other conditions which are initially set, but can be changed between runs are as follow. Initial temperature of the boiler, TEMPB, and of the vapor leaving the boiler and entering the first node, TVP(1). The pumping capacity, VPUMP, and the volume of the liquid in the boiler, VLBOIL. Also the volume of the liquid portion of the node, VNL (n) and the lifting rate of liquid from the liquid portion to the vapor portion of the node, VLIFT, can be changed.

The entire distillation tube is broke down into nodes for modeling purposes, Figure 11. Each node has a vapor stream broken down into moles of ethanol and water entering and exiting. A liquid stream of ethanol and water also enters and exits the node, but in the opposite direction

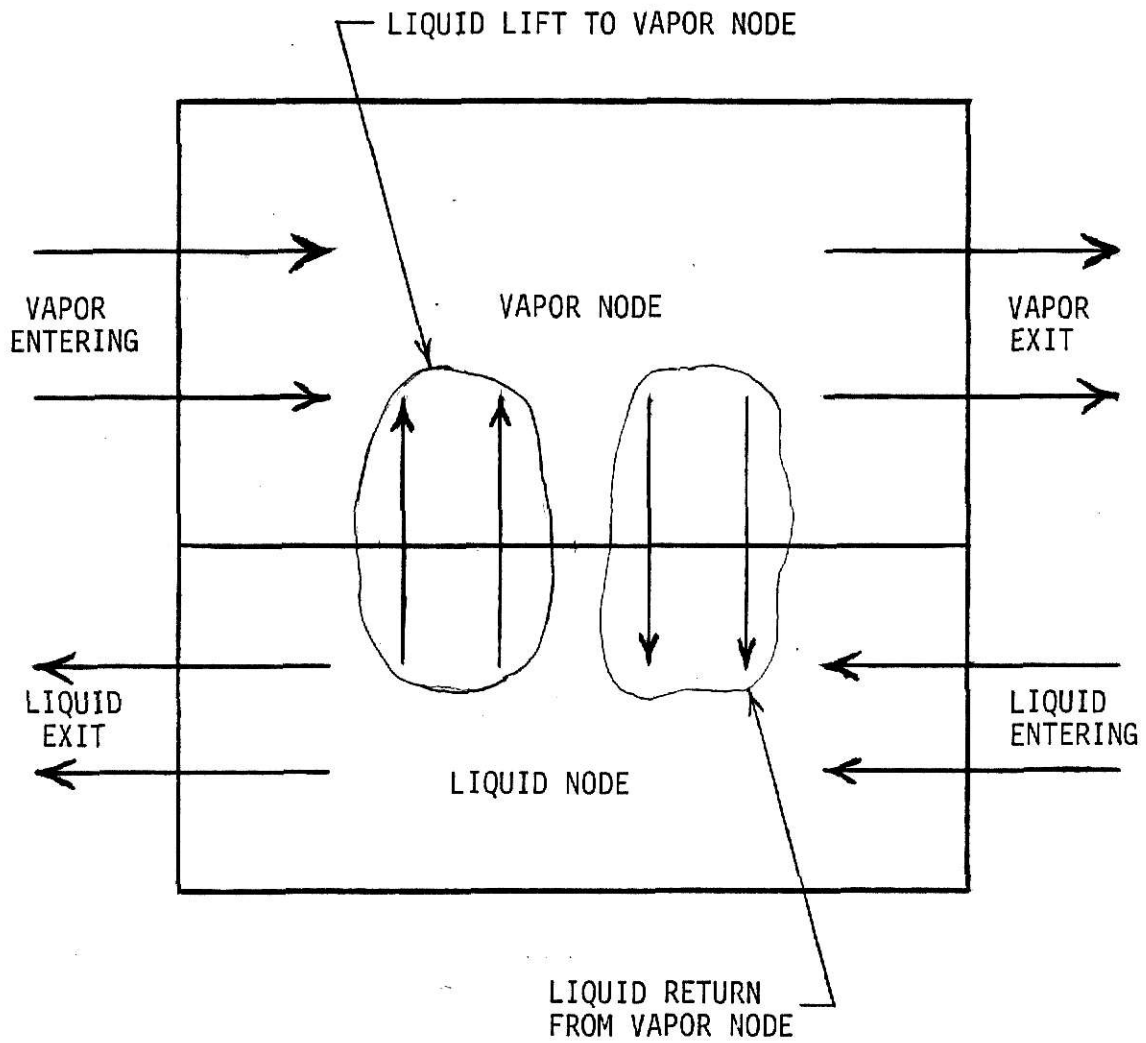


Figure 11. Breakdown of flows in a node.

of the vapor stream. Inside, the liquid is lifted into the vapor stream for mixing. It is assumed that new equilibrium conditions are established and part of the liquid falls back to the liquid portion. The entire distillation tube is broke down into either five or ten nodes, depending upon the particular run. The number of nodes used is controlled by the variable K.

MODELING OF THE DISTILLATION TUBE

The initial step in the development of the computer model was to evaluate the horizontal distillation tube. This was achieved by writing Subroutine VAPOR which calls upon Subroutines ACNODE and AFNC for support. Subroutine VAPOR is responsible for the modeling of the vapor portion of the distillation tube. In addition, Subroutine LIQUID was developed for modeling of the liquid portion of the distillation tube. The distillation tube is therefore broken down into nodes with a liquid and vapor portion as shown in Figure 12.

Vapor streams are broken down into individual components of ethanol, $NVA(n)$ and water, $NVW(n)$, entering and exiting, $NVA(n+1)$ and $NVW(n+1)$ respectively. Liquid lifted from the liquid portion of the node is also broken down into components of ethanol, $UNLA(n)$, and water, $UNLW(n)$. The liquid returning from the vapor portion of the node to the liquid portion is broken down into components of ethanol, $DNLA(n)$ and water, $DNLW(n)$. Liquid streams are also broken down into components of ethanol entering, $NLA(n+1)$, water entering, $NLW(n+1)$, and of ethanol exiting, $NLA(n)$, and water exiting, $NLW(n+1)$.

Subroutine VAPOR is responsible for combining the equilibrium, mass and energy balance calculations performed on the entire vapor portion of the distillation tube. These calculations are performed on an individual

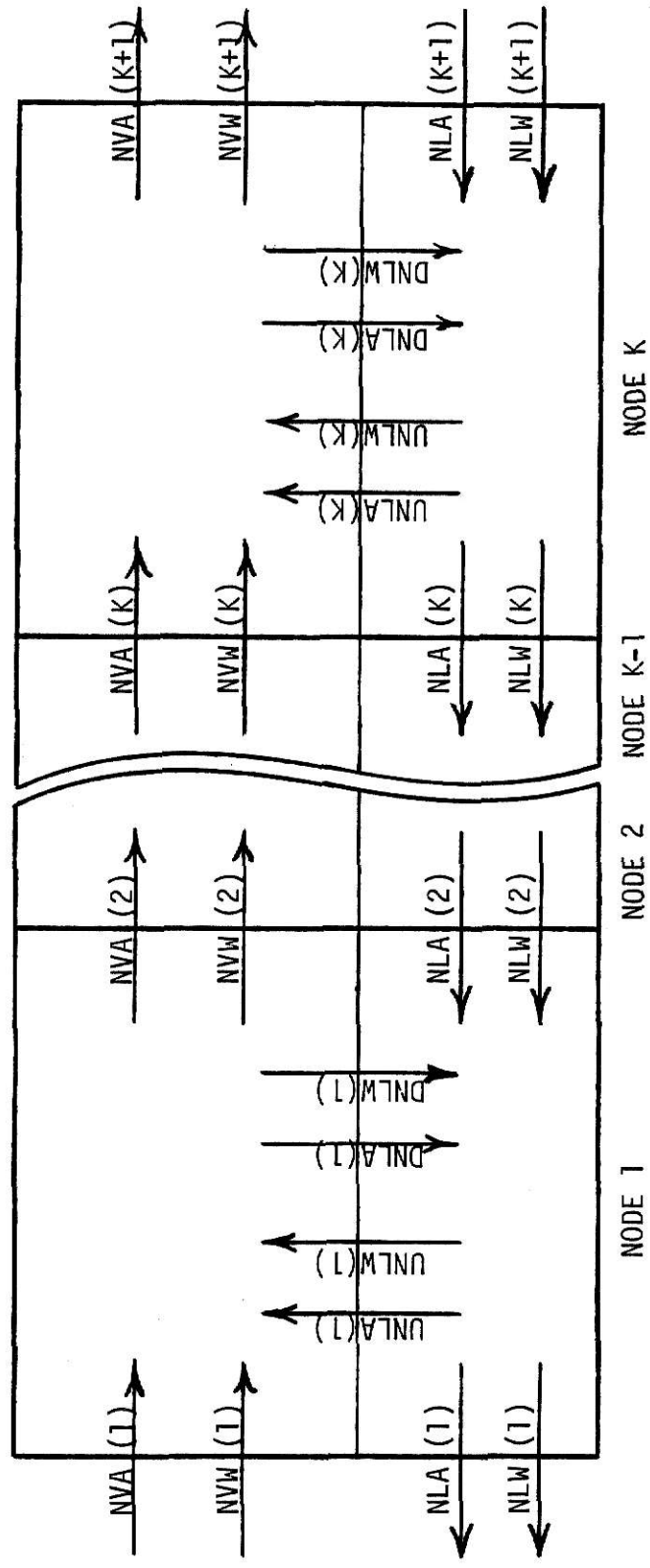


Figure 12. Representation of distillation tube in the computer model.

node basis by Subroutine ACNODE. Vapor from the boiler is supplied to the first node to start off the modeling procedure. Subroutine ACNODE is called upon to combine the vapor and liquid that enters the vapor node and determine the mass, concentration and temperature of the vapor and liquid exiting the individual vapor node. This is achieved by using Raoult's equation for equilibrium and performing an energy balance upon the flows. Subroutine AFNC is called upon to interpolate between equilibrium data supplied to the program and provide equilibrium vapor pressures for ethanol PSA, and water, PSW, at any given temperature.

In order to determine the correct temperature of the flows exiting the vapor node, a heat balance is performed. Since the latent heat of vaporization must be taken into account in the heat balance, an iterative technique is used to determine the new equilibrium temperature. A temperature range is established by the temperature of vapor, $TVP(n)$ and liquid $TLQ(n)$, entering the vapor node. The new equilibrium temperature is assumed to be within this temperature range. A binomial iteration technique of using the mean of the temperature range and establishing which half the new equilibrium temperature is within is used. A new range is then established between the mean and limit of the half that the equilibrium temperature lies. The process of halving is repeated until the temperature range has been brought to within the desired accuracy. Each time a new mean is established Subroutine AFNC is called upon to provide equilibrium vapor pressures which are used to determine the correct concentrations of vapor and liquid exiting the node. It is assumed that the vapor and liquid exiting the vapor node are at the same temperature, $DTLQ(n) = TVP(n+1)$.

Once the properties of the liquid and vapor exiting the first node have been determined Subroutine ACNODE reverts back to Subroutine VAPOR. The conditions of the first node are then stored. Subroutine VAPOR then calls back on Subroutine ACNODE to perform calculations on the second node. Conditions of vapor entering the second node are equal to those of the vapor exiting the first node.

Subroutine VAPOR repeats this process on each node until the conditions of each node and the vapor exiting the distillation tube have been determined. The volume of vapor exiting the distillation tube, VEXIT, is then compared to the volumetric capacity of the pump, VPUMP. If the exit volume is too large or small a binomial iteration technique is used to correct the amount of vapor entering the distillation tube from the boiler. Subroutine VAPOR then repeats the calculation on the vapor portion of the distillation tube to determine the new exit volume. This is repeated until the exit volume is within the desired accuracy of the pumping volume. The amount of vapor entering, NVA(1) and NVW(1), and exiting, NVA (K+1) and NVW(K+1), are then known. Temperature of the vapor exiting, TVP(K+1) is also known.

After the new conditions are established for the vapor portion of the distillation tube, Subroutine LIQUID is called. Subroutine LIQUID performs a volume, mass and energy balance on the liquid portion of the distillation tube. The liquid node maintains a constant volume throughout the modeling process. At initial start up it is assumed that total reflux takes place. This is necessary during the initial stage of operation to bring the exit concentration up to the desired level.

Subroutine LIQUID starts with the last node, K, and performs a volume, mass and energy balance. The input variables known are liquid refluxed, $NLA(K+1)$ and $NLW(K+1)$ which are equal to $NVA(K+1)$ and $NVW(K+1)$ except that the vapor has been condensed. Liquid lifted to the vapor portion of the node, $UNLA(K)$ and $UNLW(K)$, and liquid returned, $DNLA(K)$ and $DNLW(K)$, are also known. The temperature of liquid entering the node is also known. It is assumed that liquid exiting the node is at the liquid node temperature, $TLQ(K)$, because the mass of liquid entering and exiting the node is small compared to the mass of liquid stored during the time period.

A volumetric balance is performed on the Kth node to determine the amount of ethanol and water exiting the Kth node and entering the K-1 node, $NLA(K)$ and $NLW(K)$. Then a mass balance is made to determine the new concentration of the liquid node. The concentration of liquid exiting the node is assumed to be at the concentration of the node before the mass balance is performed. Next, an energy balance is made to determine the new temperature of the liquid node, $TLQ(K)$.

Subroutine LIQUID repeats the above calculations on each liquid node of the distillation tube starting with the Kth node and working down to the first node. Once complete, the amount of liquid exiting the distillation tube, $NLA(1)$ and $NLW(1)$, and temperature, $TLQ(1)$, are known. The amount of liquid entering the node as reflux is controlled by the MAIN program. This will be discussed in the section dealing with the MAIN program.

SUBROUTINE BOILER

Subroutine BOILER is called upon next. It performs a mass balance and energy balance upon the boiler. The amount of vapor exiting the boiler, $NVA(1)$ and $NVW(1)$, and liquid returning from the distillation tube,

NLA(1) and NLW(1), are known from the previous subroutines. The temperature of liquid returning from the distillation tube, TLQ(1), is also known. It is assumed that the boiler is initially loaded as a batch boiler with a given amount of liquid ethanol and water, BLA1 and BLW1.

Subroutine BOILER first performs a mass balance upon the ethanol and water that exit and enter the boiler. This balance determines the new concentration of liquid ethanol in the boiler, XAB2. It is assumed that the concentration of vapor entering the distillation tube is equal to the concentration of vapor in the boiler before the mass balance on the boiler is performed. Subroutine AFNC is called upon to supply equilibrium data. A binomial iteration similar to the one used in Subroutine VAPOR is used to determine the new boiling temperature of liquid in the boiler at the new concentration determined by the mass balance. An energy balance is then performed to determine the heat energy input, QADDBL, necessary to vaporize sufficient liquid to supply the distillation tube.

SUBROUTINE PUMP

The next step calls Subroutine PUMP to provide information on the compression of the vapors exiting the distillation tube. It is assumed that the ethanol and water vapor behave as an ideal gas. The compression process is assumed reversible and adiabatic with constant specific heat. A value for the ratio of specific heat, k is determined by

$$k = \frac{C_{Pexit}}{C_{Pexit} - R} \quad (13)$$

The specific heat capacitance, C_{pexit} , is determined from a weighted averaging of the individual specific heat capacitance of ethanol and water vapor entering the pump.

Work required to compress one mole of vapor, WKPUMP, from the distillation tube pressure to atmospheric pressure is determined by

$$WKPUMP = \left[\left(\frac{P_2}{P_{ST}} \right)^{\frac{k-1}{k}} - 1.0 \right] \frac{R(TVP(K+1))}{\left(\frac{k-1}{k} \right)} \quad (14)$$

The temperature of vapor exiting the pump, TEMP2P, is then determined by the ideal gas law equation

$$TEMP2P = TVP(K+1) \left(\frac{P_2}{P_{ST}} \right)^{\frac{k-1}{k}} \quad (15)$$

Subroutine PUMP also provides information on the amount of energy available to the boiler. It is assumed that the compressed vapor, which is at a higher temperature than liquid in the boiler, enters a heat exchanger located in the boiler. The vapor is allowed to condense in the heat exchanger, thus releasing the heat of vaporization it contains. Subroutine AFNC is called upon to provide the equilibrium temperature, TEMPEQ, corresponding to the concentration of the condensed vapors at atmospheric pressure. It is assumed that the vapor condenses to its equilibrium temperature, TEMPEQ, which is still greater than the boiler temperature, TEMPB. A difference in the enthalpy of vapor entering and liquid exiting the boiler through the heat exchanger is made. This difference indicates the amount of heat energy available to the boiler, QAVAL. If QAVAL is greater than the heat requirement of the boiler, QADDBL, then sufficient energy for distillation exists.

MAIN PROGRAM

The MAIN PROGRAM serves to initialize the conditions of the system and then maintain the order of execution of the subroutines. In the first part of the Main Program, conditions for start up are initialized. The program then enters a loop to perform all the calculations on the distillation system. Each loop is considered to be an increment of real time which is set at 0.005 hr at start-up and then changed to 0.02 hr after 200 loops. The results obtained after each loop provide the new condition for the next loop. A series of print statements are encountered after the program has returned from the last subroutine. The Main Program can then print the results of the loop, but a counter is provided so that results are printed only every 50th loop.

After the print statement is an algorithm to adjust the reflux rate. During start-up total reflux takes place. Once the designed concentration is achieved part of the solution is removed from the system. This algorithm regulates the reflux needed to maintain the desired concentration.

The results of the computer model are present in Chapter 4.

CHAPTER III

PHYSICAL MODEL

The second objective was to evaluate the proposed distillation system by building a working model. Construction of this model took place in the shop area of the Department of Mechanical Engineering. Assembly was completed by the author with assistance from technicians of the department. Basic components of the system consist of a boiler, distillation tube, screen lifting mechanism, compressor, and heat exchangers.

The boiler, Figure 13 and bottom of Figure 14, was fabricated from a 10-inch diameter steel pipe approximately 10 feet long. A steel flange and cap were placed on one end. The other end was welded shut. Pipe connections were provided for vapor flow between the boiler and the distillation tube, heat exchanger connections, and provisions for filling and emptying the boiler were also provided.

Inside the boiler is a heat exchanger, Figure 15, approximately 60 feet of 5/8-inch copper tubing. This provided for about 9.8 square feet of heat exchange area. Connections of 1/2-inch pipe through the end plate permitted passage of fluids in and out of the heat exchanger.

The distillation tube, Figure 13 and top of Figure 14, was fabricated from a 10 foot piece of Schedule 40 Poly Vinyl Chloride pipe, (PVC), 8 inches in diameter with 3/8-inch thick walls. End plates were fabricated from 3/8-inch thick sheet PVC and attached with a flange configuration. PVC pipe fittings were mounted on the distillation tube to permit connections to the boiler, exit of vapor to the compressor, and return of liquid for reflux.

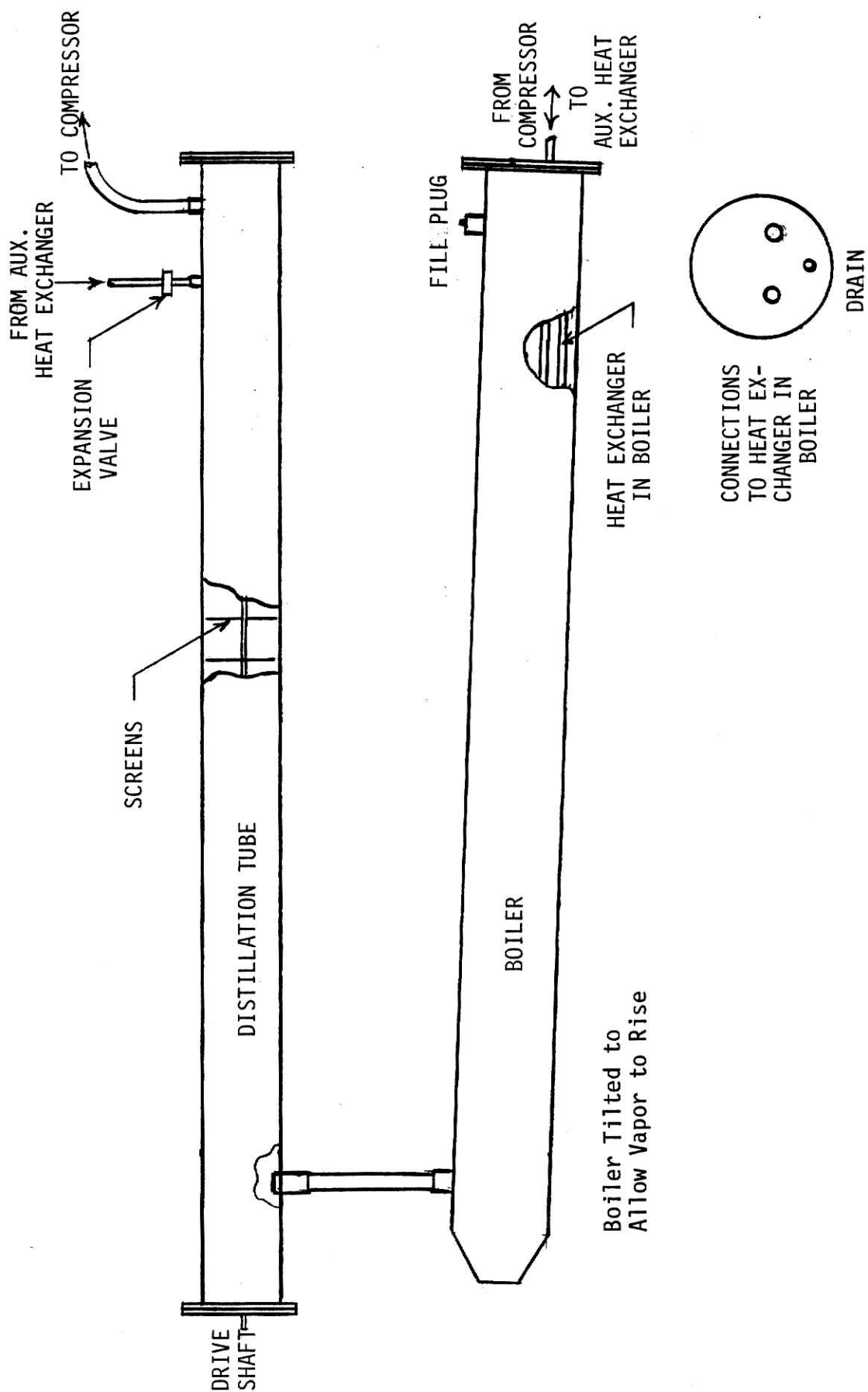


Figure 13. Drawing of boiler and distillation tube.



Figure 14: Distillation tube, (top), boiler, (middle), and auxiliary heat exchanger, (bottom), early in construction.

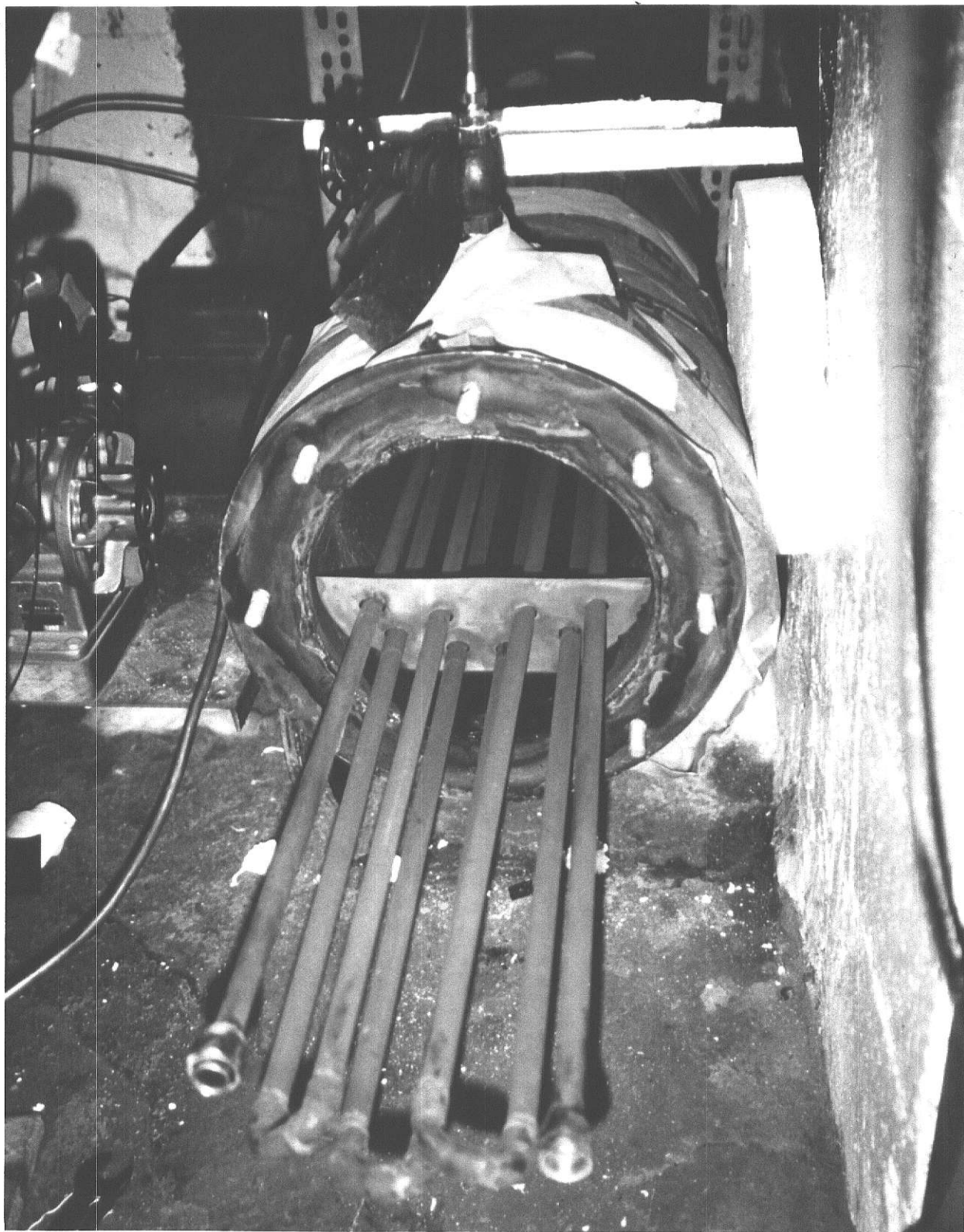


Figure 15. Heat exchanger located in boiler.

Included in the distillation tube is a mechanism for lifting liquid from the bottom portion of the distillation tube into the vapor flowing through the tube, Figure 16. This is achieved by rotating a series of screen on a shaft. Rotation of the screens can be varied from 10 to 25 revolutions per minute by changing pulleys. The screens are made of fiberglass screen sandwiched between two metal plates. These metal plates are slightly smaller than the inside tube diameter. The plates have a 3/4-inch rim. One of the plates is connected to the rotating shaft by 3 spokes that are 3/4-inches wide. The two metal rims are screwed together with the screen placed between. Attached to the rim are three copper tubes approximately 8 inches long that are curved to the contour of the tube. One end has a U-bend to allow for the dumping of liquid across the screen as it rotates. The screens were placed on a keyed shaft fabricated from 5/8-inch rigid copper pipe. Pieces of 1/2-inch PVC pipe were placed over the shaft between the screens to act as spacers. The screens are rotated by an electric motor mounted outside the distillation tube. A series of pulleys reduce the speed and the power is transmitted through a shaft that passes through a seal in the end plate. A planetary gear inside the tube reduces the shaft speed to the desired speed before turning the screens.

Connection between the boiler and the distillation tube was achieved by a 1 1/4-inch diameter PVC pipe. A short piece of 1 1/4-inch PVC pipe is attached to the PVC pipe fitting inside the distillation tube so that it rises 3/4-inches above the bottom of the distillation tube. This allows for a constant liquid level in the distillation tube. When the liquid rises above this tube it flows down the inside wall of the pipe into the boiler. Vapor from the boiler is allowed to flow through the center of

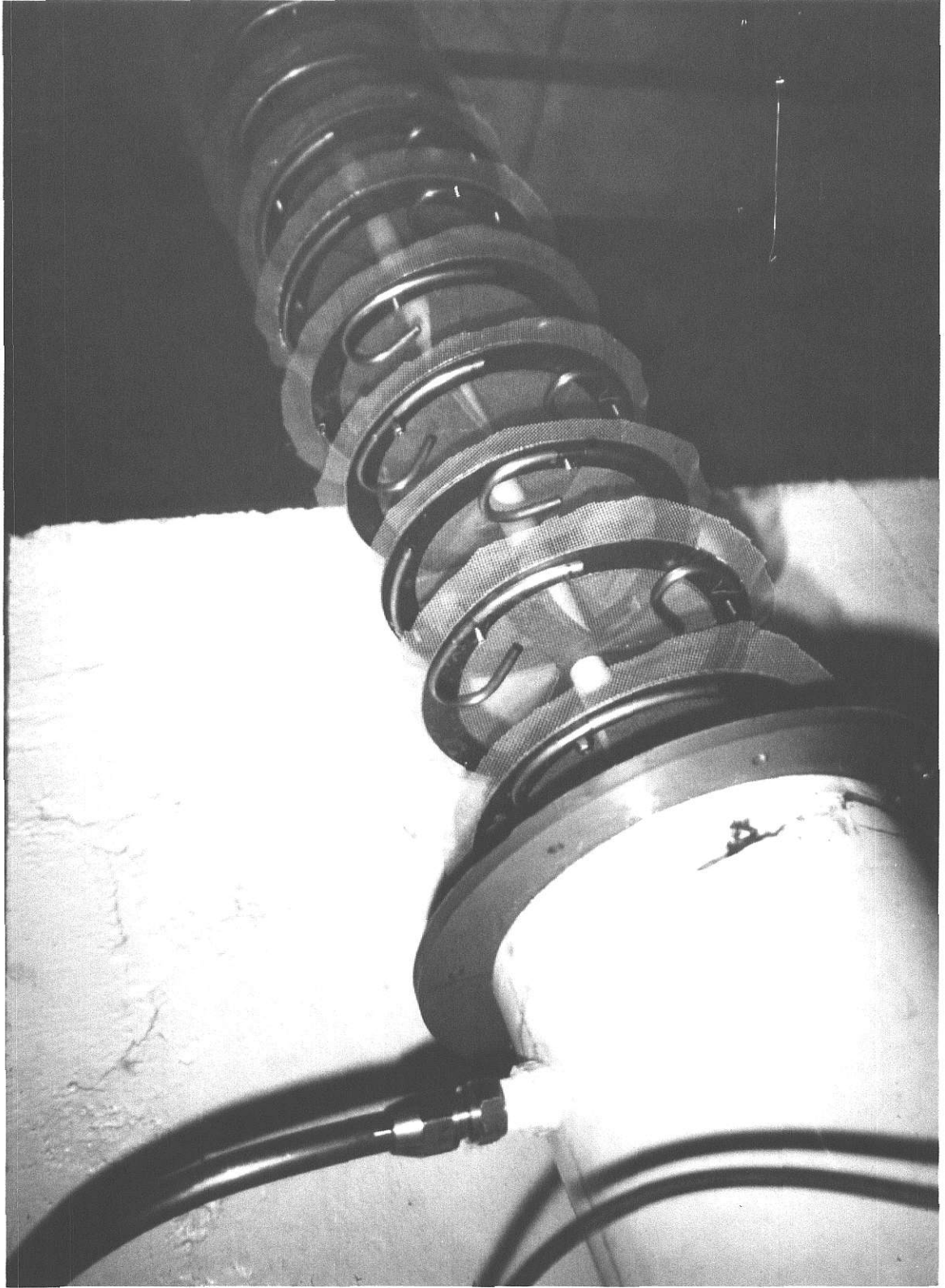


Figure 16. Screens on shaft located in distillation tube.

the PVC pipe.

The compressor used is a GAST model 2565-V2 Rotary Vane vacuum pump, pictured at the bottom of Figure 17. It is rated at 21 s.c.f.m. of air flow at zero inches of mercury and can pull a maximum of 28 inch Hg vacuum. Connection is made to the distillation tube on the low pressure side of the pump with 5/8-inch copper tubing. The high pressure side of the pump is connected to the heat exchanger in the boiler by 3/4-inch iron pipe.

An auxiliary heat exchanger is connected to the exiting line of the heat exchanger in the boiler by a 1/2-inch copper tube. The auxiliary heat exchanger is a finned tube heat exchanger comprised of a 100 foot length of 1/4-inch copper tubing. This heat exchanger completes the condensation of any vapor that may exit the boiler heat exchanger and reduces the temperature further once it is liquid.

The liquid exiting the auxiliary heat exchange flows through a 3/8 inch copper tube into an accumulator. This accumulator allows for the separation of any air that may be in the liquid. The liquid then passes through a flow meter and a set of valves controls the flow either out of the system for recovery or back into the distillation tube through an expansion valve for reflux. An expansion valve is attached to the top of the distillation tube upon a PVC fitting provided. Connection between the valves and expansion valve are made by 1/4-inch copper tubing.

INSTRUMENTATION

In order to evaluate the physical model certain properties must be monitored. Temperature, pressure, concentration and flow rates are monitored and recorded during the experiment. Thermocouples are placed at thirteen different locations as shown in Figure 18. These are recorded on

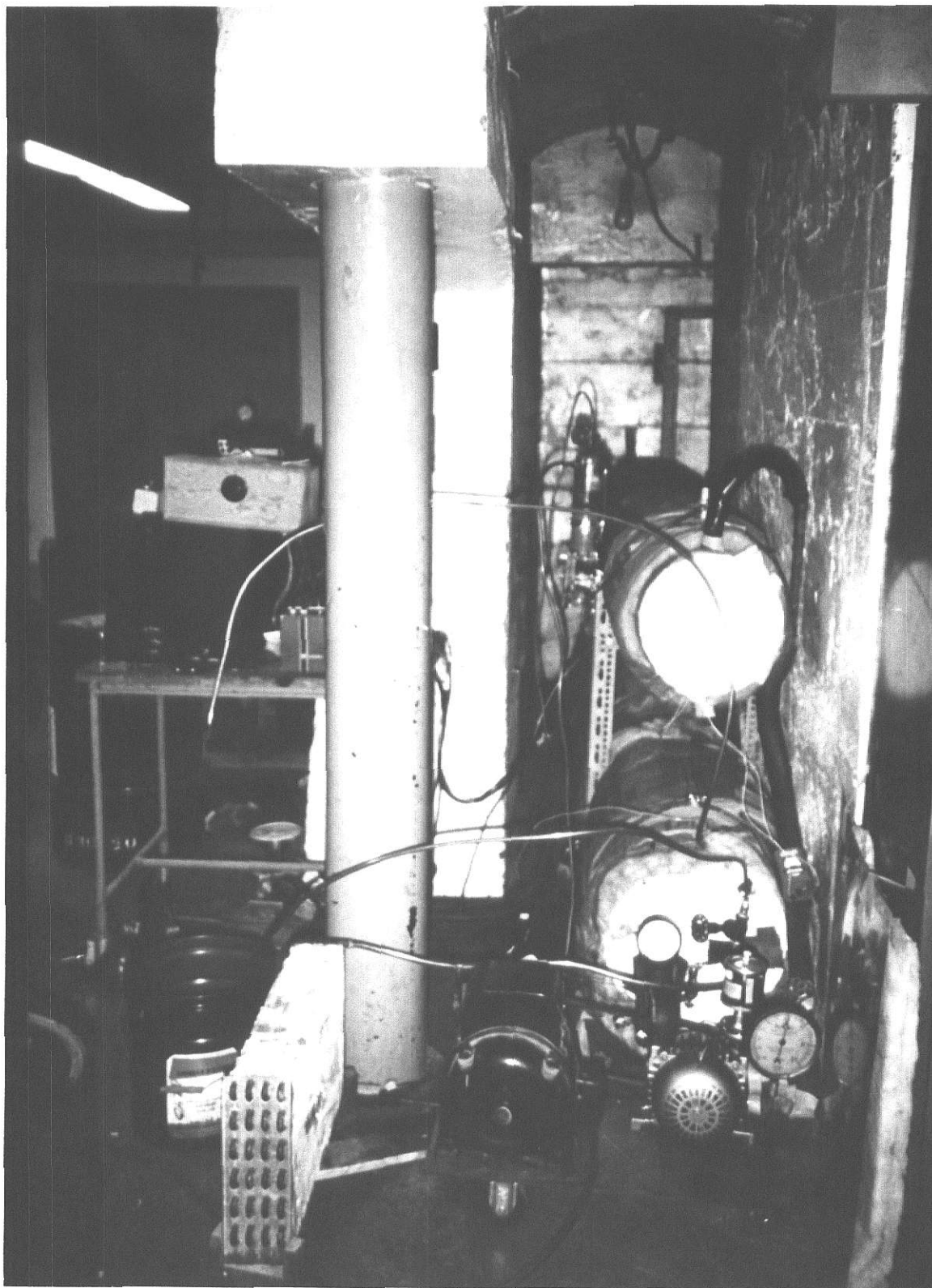


Figure 17. End view of distillation system.
Pump located at bottom in front of boiler.

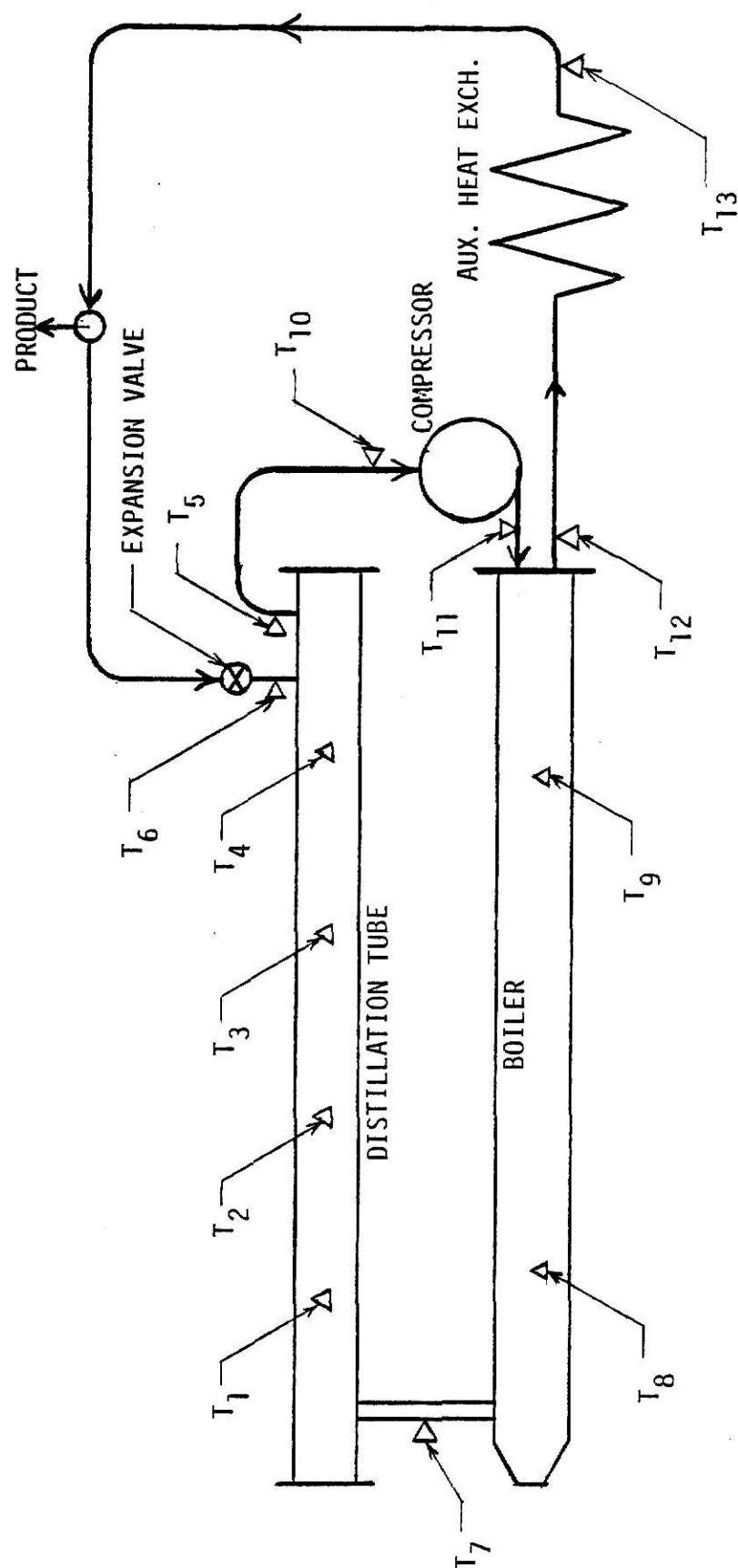


Figure 18. Schematic of thermocouple locations.

a Honeywell Brown milli-volt recorder, Figure 19, at half hour intervals throughout the experiment. Pressure gauges are located on the high and low side of the pump. These gauges are monitored and values recorded at half hour intervals. The amount of work into the system is monitored by watt meters that measures the electrical input to the electric motor driving the vacuum pump, the screen rotating motor and the electric heat tapes used to compensate for heat losses. These watt meters are monitored and recorded every half hour.

To determine the concentration of the ethanol-water solution exiting the system a sample is removed every half hour. The sample is placed in a glass tube where an alcohol hydrometer is used to measure the ethanol content. A sample from the boiler is removed every hour and measured with a hydrometer to determine the concentration of the raw ethanol-water solution.

A flow meter is located in the reflux line to indicate the approximate flow rate of liquid refluxed into the distillation tube. Ethanol-water solution that is removed from the system, once it is of sufficient strength, flows into a container. Each half hour the container is changed and the contents measured with a graduated cylinder and recorded.

EXPERIMENTAL PROCEDURE

To operate the distillation system, an initial temperature must first be established. Heat tapes wrapped around the boiler, heat the liquid solution to approximately 140°F. Once this temperature is achieved the pump is started. The motor turning the screens is also started. A valve located on the high side of the pump is opened to allow air in the system to escape as the pressure is reduced. The valve between the low side of the pump and the distillation tube is then opened. The valve on

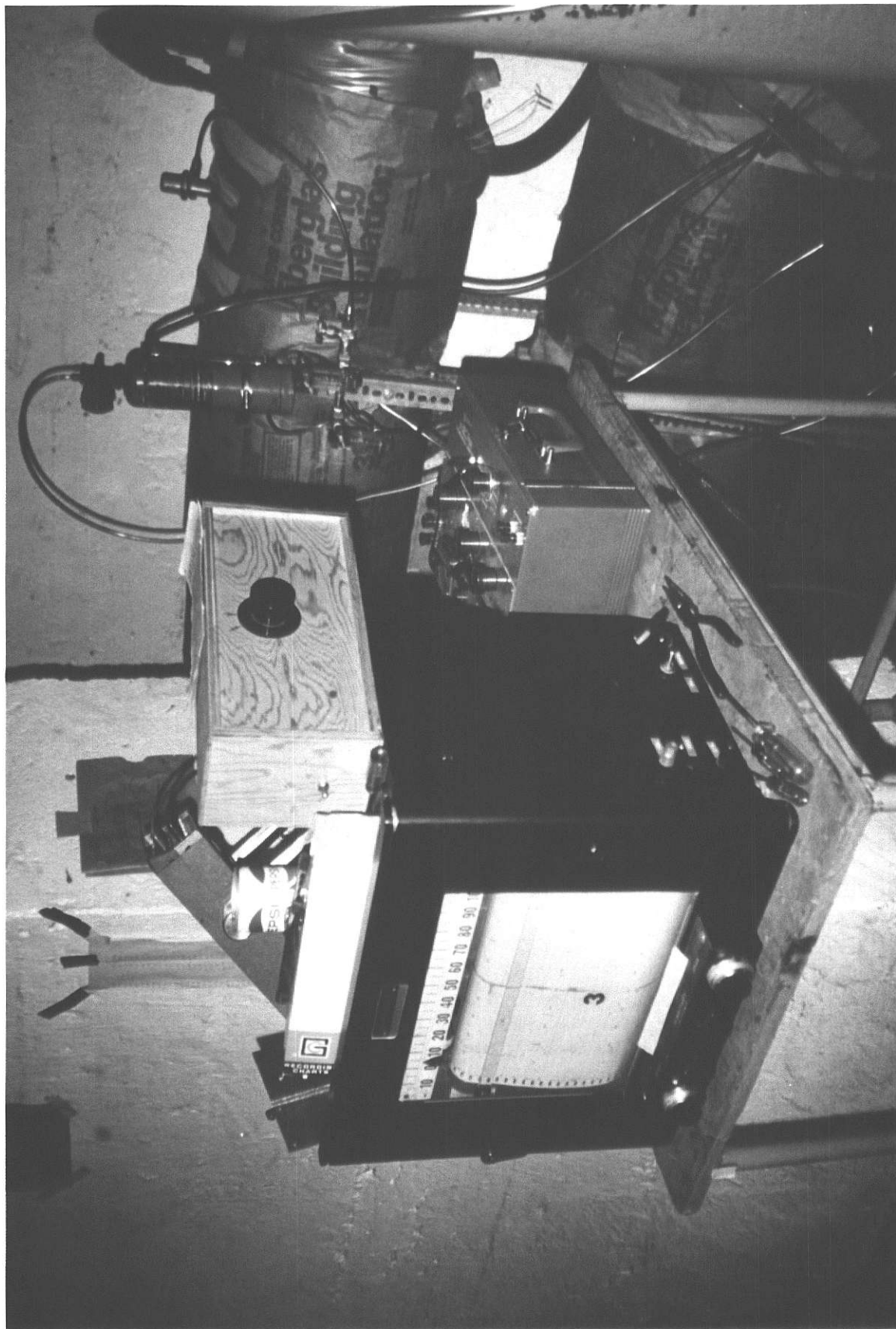


Figure 19. Milli-volt recorder, (left), and distillation system, (right). Accumulator located on stand beside distillation tube.

the reflux line is closed until sufficient liquid is in the accumulator to be refluxed. After approximately 5 minutes the valve releasing air on the high side of the pump is closed. Any remaining air can then escape through the accumulator.

Once sufficient liquid is in the accumulator, the reflux valve is opened. It is adjusted so the level of liquid in the accumulator remains constant. The accumulator should have sufficient liquid after 15 to 30 minutes of operation. Total reflux takes place until the concentration of liquid being refluxed has reached the desired level. This takes approximately 1 1/2 to 3 hours after start-up. Part of the liquid is then diverted to a container outside the system. This is achieved by allowing the accumulator to fill up and overflow. A pipe from the accumulator overflow diverts liquid to a container outside the distillation system. The reflux valve is adjusted so that the flow meter reads approximately 3/4 of the total reflux valve. Therefore approximately 3/4 of the liquid flow is refluxed and the remaining 1/4 is removed from the system as product.

The distillation system is allowed to run until the concentration of the product drops below the desired level. By increasing the amount refluxed, the concentration can be increased, but once the boiler concentration becomes very low (i.e. less than 2 or 3% volume ethanol), it becomes impractical. During the entire run data is taken at half hour increments to monitor the operation. Most runs lasted approximately 12 to 14 hours.

CHAPTER IV

RESULTS

RESULTS OF COMPUTER MODEL

The results from the computer model described in Chapter II indicated that the proposed distillation system would work. Many different parameters were used during the course of running the model. Ideal conditions were assumed throughout the program in mixing of vapor and liquid, equilibrium, and pump work. It was also assumed that no heat loss took place between the boiler and distillation tube to the surroundings.

Numerical stability of the computer model was affected by changes in the pumping capacity, VPUMP, and liquid lifting rates, VLIFT, in the distillation tube. The time increment, DT, was decreased when the pumping capacity and lifting rates were lowered to maintain stability.

In order to have an indication as to the performance of the operation of the distillation system, a ratio of the heat of combustion available in the ethanol distilled to the work input to the pump was used.

$$\text{Performance Ratio} = \frac{\text{Heat of Combustion} \times \text{Ethanol Recovered}}{\text{Total Work into Pump}} \quad (16)$$

This ratio was plotted against time to help determine the performance of the distillation during its operation.

In the running of the computer model, a major observation made was that at a system pressure of eight pound per square inch, (8psia), the compression process of the vapor did not increase the available energy enough to supply the boiler with sufficient heat to maintain distillation with the exit pressure at 1 atmosphere. Once the system pressure was reduced to six psia, the compression process was then sufficient to maintain the

energy input required by the boiler.

Figures 20 and 21 present graphs of results from the computer model.

The parameters used in the model for these graphs are as follow:

Initial concentration of Boiler	5 Mole percent ethanol
Amount of Ethanol in Boiler	0.44 lb moles
Amount of water in Boiler	8.25 lb moles
Initial temperature of Boiler	150°F
Pump capacity	600 ft ³ /hr
Volume of each liquid node	0.006 ft ³
Lifting rate of liquid in each node	0.9 ft ³ /hr
Pressure of distillation system	4 psia
Time increment	0.02 hr

In Figure 20 the boiler concentration, exit concentration, (in percent volume ethanol), total volume recovered, volume ethanol recovered, and performance ratio are plotted against time. Temperature at various points across the distillation tube and of the boiler and vapor exiting the pump are plotted against time in Figure 21.

By examining Figure 20 it is seen that the performance of the distillation peaked out approximately 8 hours after start-up. After that time it gradually dropped off. In the first 24 hours the boiler dropped almost 6 percent in concentration. During the next 24 hours though, it only dropped 1.7 percent. The rate of recovery dropped off just as much. During the first 24 hours a total of 5.4 liters was recovered. The next 24 hours produced only 1.6 liters.

Examining the temperature profile in Figure 21 it is noted that temperatures at the different locations remain constant once the distillation system reached steady state. A steady state condition was achieved within the first hour of operation. Temperatures T_1 through T_5 indicate the temperature profile that exist along the distillation tube. These temperature locations are analogous to those in Figure 18 of Chapter III.

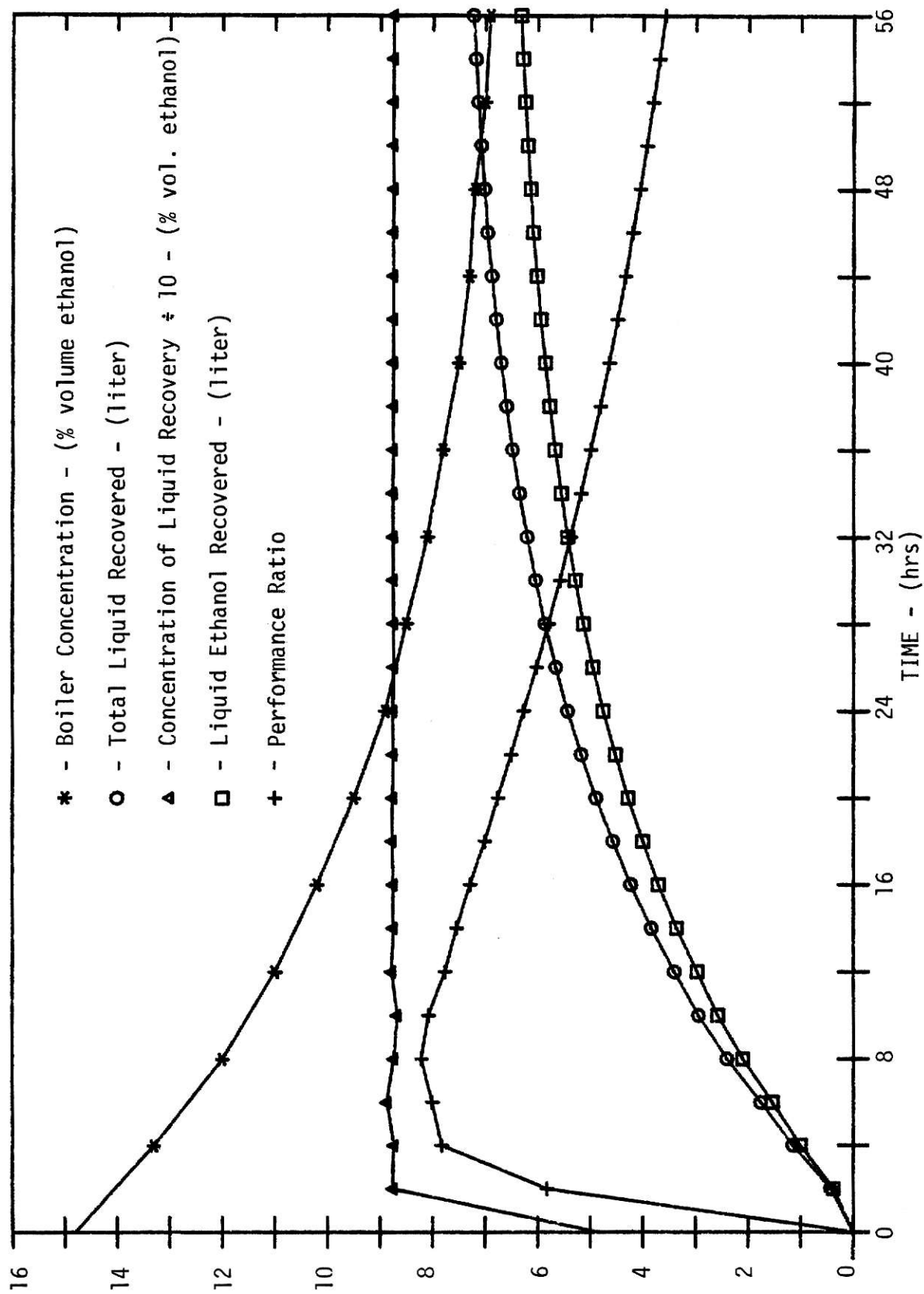


Figure 20. Graph of concentrations, efficiency ratio, and amount of recovery from computer model.

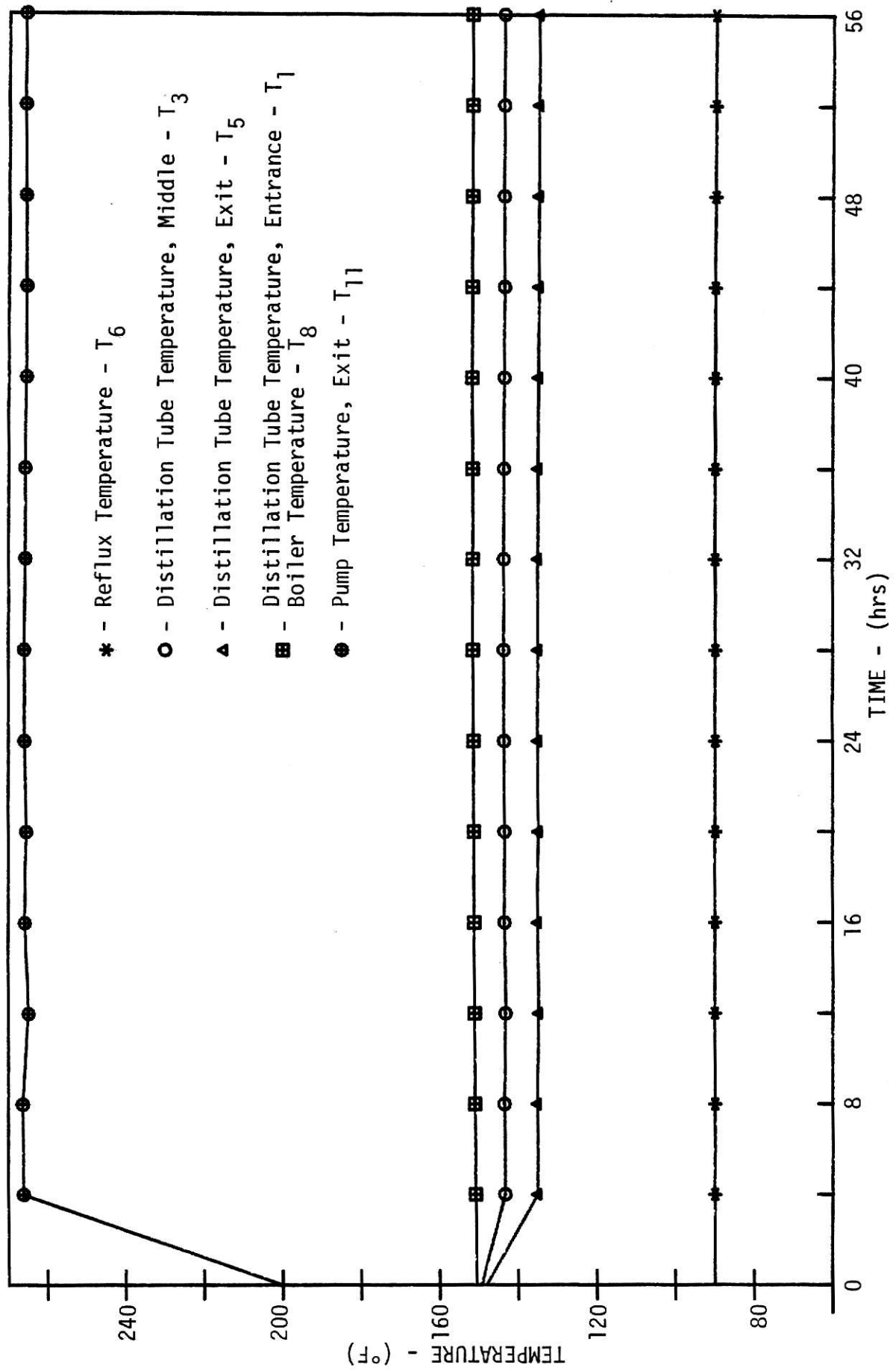


Figure 21. Graph of temperatures from computer model.

EXPERIMENTAL RESULTS

Once the model described in Chapter III was constructed, four experimental runs were made. The first experiment ironed out the experimental procedure used and resulted in limited data. In the third experiment, equipment failure early in the experiment resulted in premature shutdown thus providing incomplete data. The second and fourth experimental runs were successful in data acquisition. Results of the second experiment are present in Figures 22 and 23. In Figures 24 and 25 the results from the fourth and final experiment made by the author are presented. Each of these experiments basically followed the procedure described in Chapter III.

Figure 22 and 24 plot the boiler concentration, exit concentration, (in percent volume ethanol), total liquid recovered, amount of ethanol recovered in the liquid and the ratio of heat of combustion to work input as a function of time during each experimental run. Temperatures at various location in the distillation system are plotted against time in Figure 23 and 25 for each experimental run.

Second Experimental Run

In the second experiment, Figures 22 and 23, a fan supplied air across the secondary heat exchanger for the first four hours of the experiment. When the fan was shut off an increase in the reflux temperature was noted. This was due to the decrease in air flow across the auxiliary heat exchanger.

Approximately eight hours into the experiment, the amount of liquid recovered was significantly reduced. This was done in an effort to increase the exit concentration of the liquid by increasing reflux to almost 100

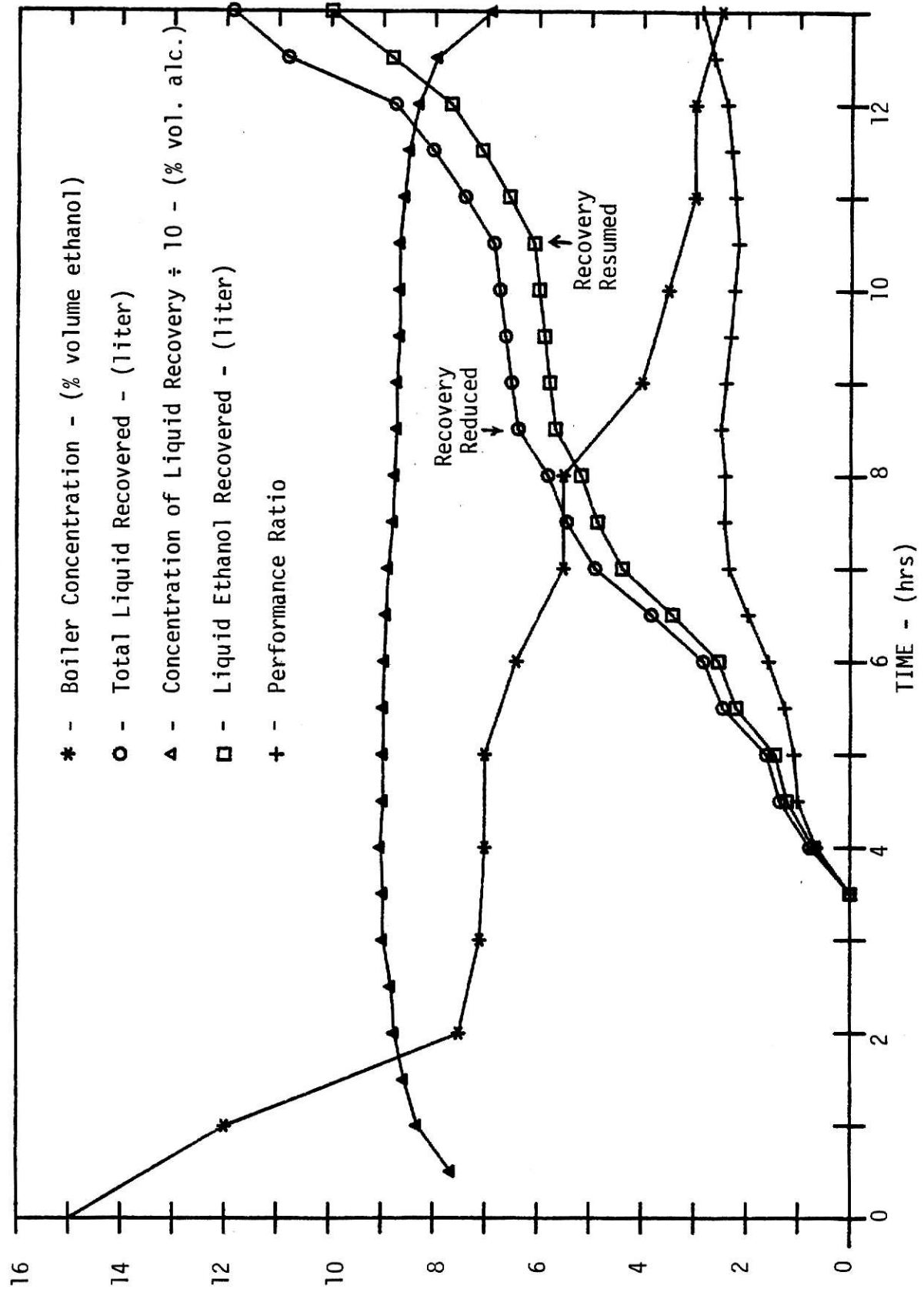


Figure 22. Graph of concentrations, efficiency ratio, and amount of recovery from experiment two.

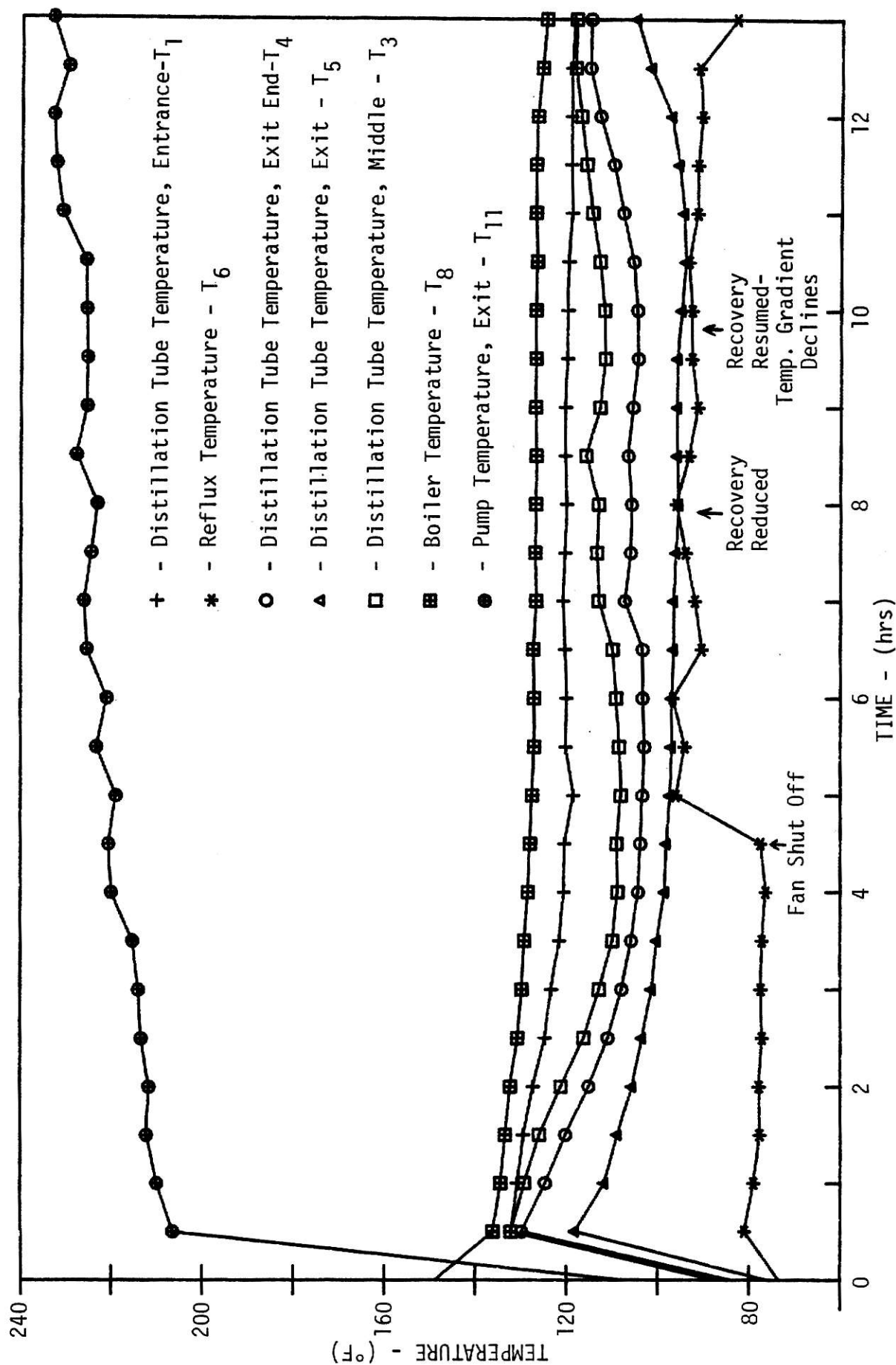


Figure 23. Graph of temperatures from experiment two.

percent. The exiting concentration leveled out during this period of almost total reflux. But as soon as a higher rate of recovery started the exit concentration fell dramatically. This was due mainly to the low concentration of ethanol in the boiler at this stage of the experiment.

About 11 hours into the experiment the temperature gradient in the distillation tube began to decrease. This continued until the end of the experiment at which time the temperature in a majority of the distillation tube was nearly equal. This was an indication that the boiler concentration had become so low, that the separation process could no longer be carried out as during the rest of the experiment.

Fourth Experimental Run

During the fourth experimental run the rate of liquid recovery was held constant. This increased the performance ratio over the second experimental run where reflux was not held constant, Figure 24. The boiler concentration increased at two hours into the experiment. This can be attributed to experimental error and possibly the lack of complete mixing of the liquid in the boiler.

At approximately four hours into the experiment a minor mechanical problem stopped the rotation of the screens. The pump continued to operate. As a result of the stoppage of the screen, it was noted that the exit concentration decreased. A decrease in the temperature gradient across the distillation tube also resulted during the stoppage, Figure 25. The screens did not rotate for approximately one half hour. Once the rotation resumed the exit concentration and temperature gradient returned to steady state conditions. This occurrence indicated that the rotation of the screens was

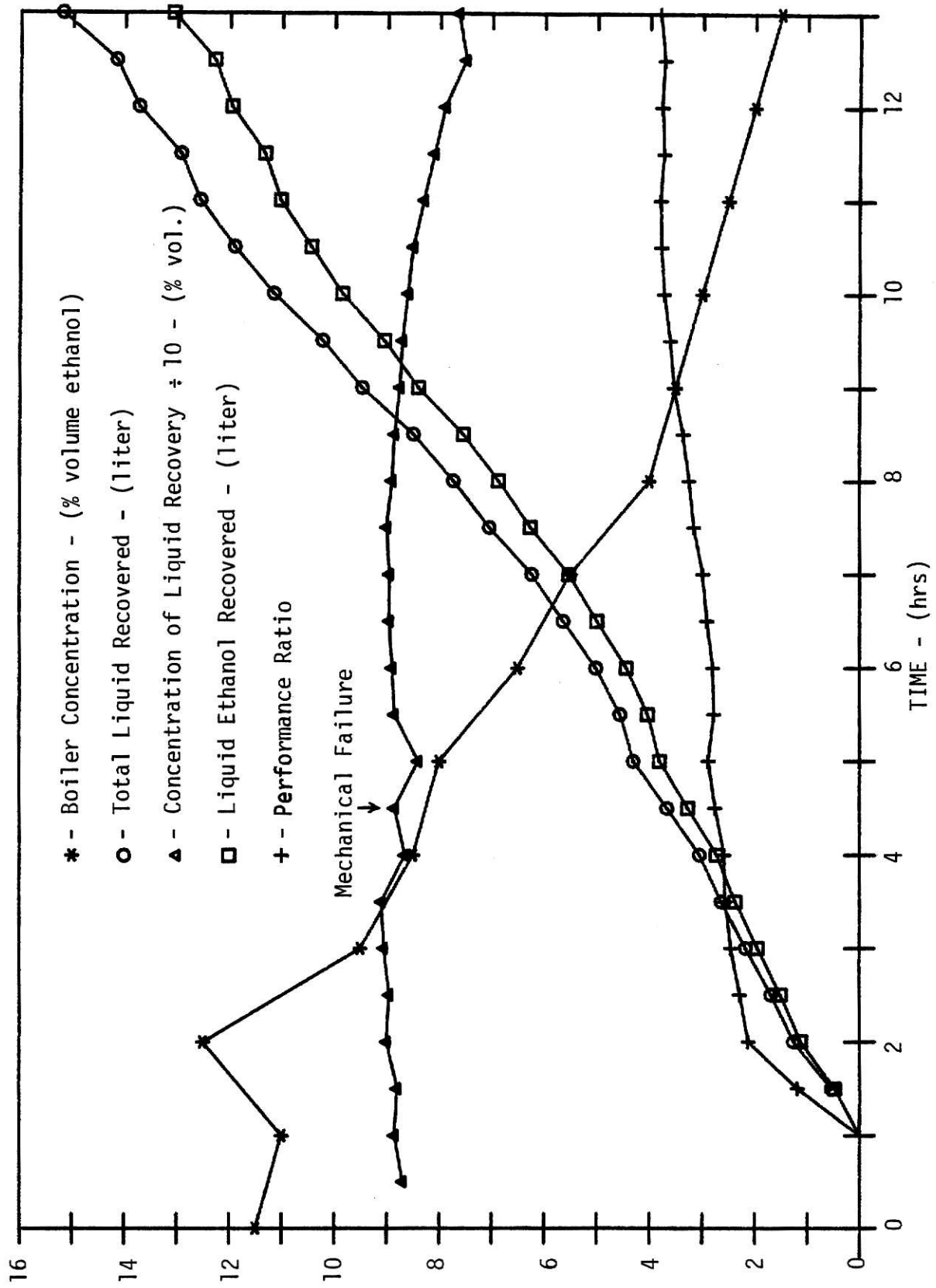


Figure 24. Graph of concentrations, efficiency ratio, and amount of recovery from experiment four.

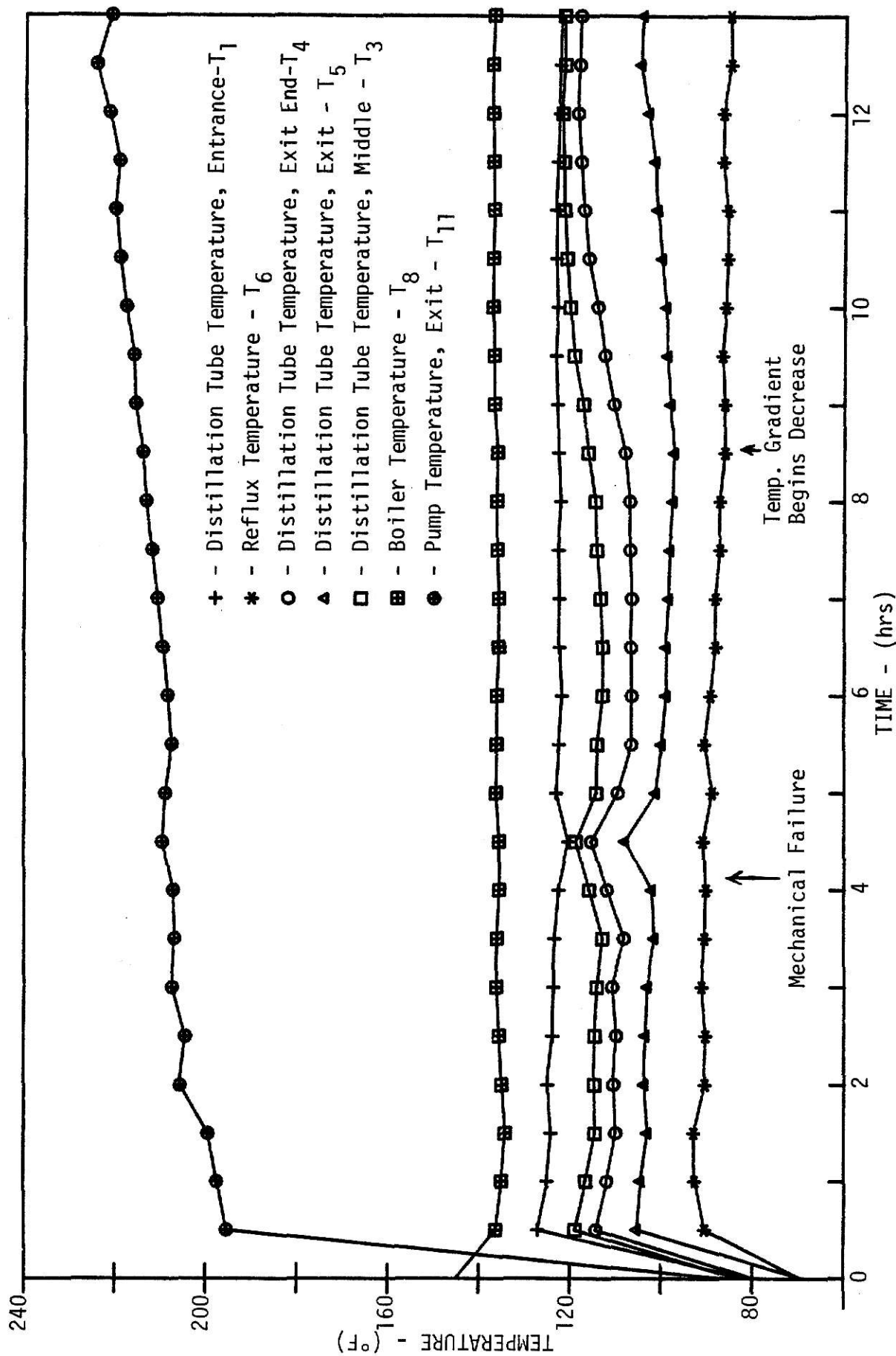


Figure 25. Graph of temperatures from experiment four.

responsible for the separation process.

The boiler concentration and exit concentration in the fourth experiment behaved similar to that of the second experimental run as the experiment approached the end. A decrease in the temperature gradient was again noted during the last few hours of the experiment, Figure 25.

The performance ratio, as defined in the section on the computer model results, was higher in the fourth experiment than the second. This was due to the constant withdraw of product that took place in the fourth experiment. In the second experiment there was a period of total reflux during the middle of the experiment. This period of total reflux had a substantial effect on the performance ratio.

CHAPTER V

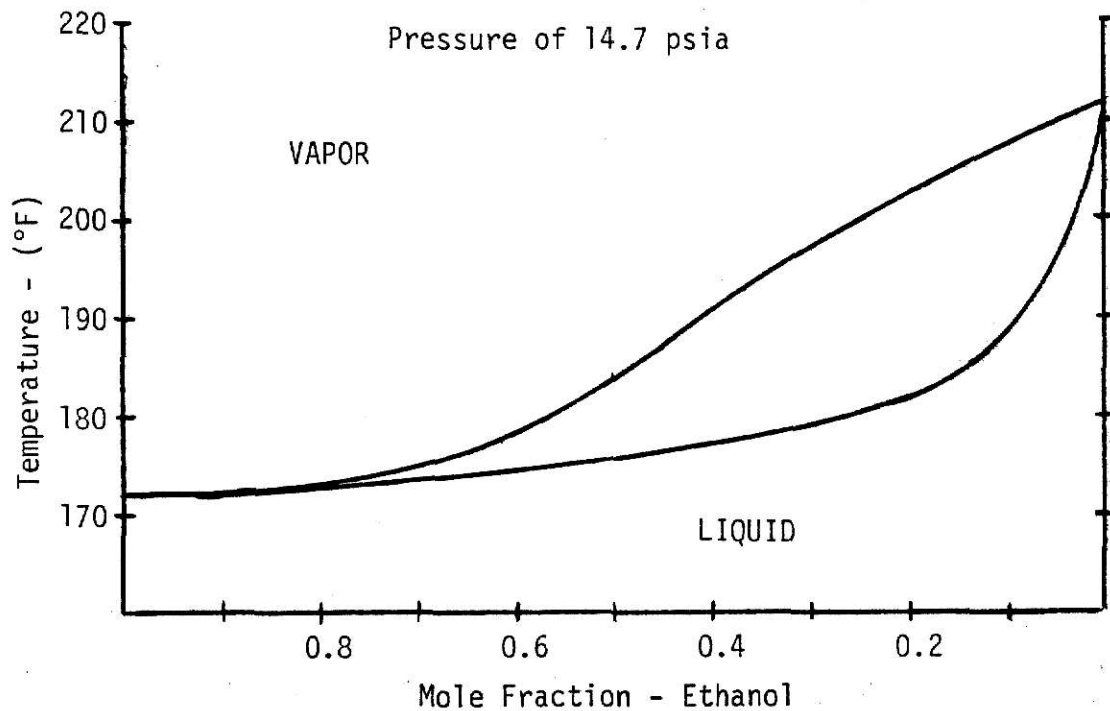
DISCUSSION

Comparing the computer model with the physical model, it is immediately seen that the period of distillation was much longer in the computer model than in the physical model. This was probably due to several reasons that are not all apparent. The main reason that was first apparent is the difference between the actual phase equilibrium diagram for ethanol-water and the ideal equilibrium assumed in the computer model, Figure 26. Ethanol is actually more volatile than indicated in the ideal phase equilibrium diagram. Liquid at a concentration of 5 mole percent ethanol will vaporize at a concentration of 32 mole percent ethanol. When ideal equilibrium is assumed though, the concentration of the vapor will only be 10 mole percent ethanol.

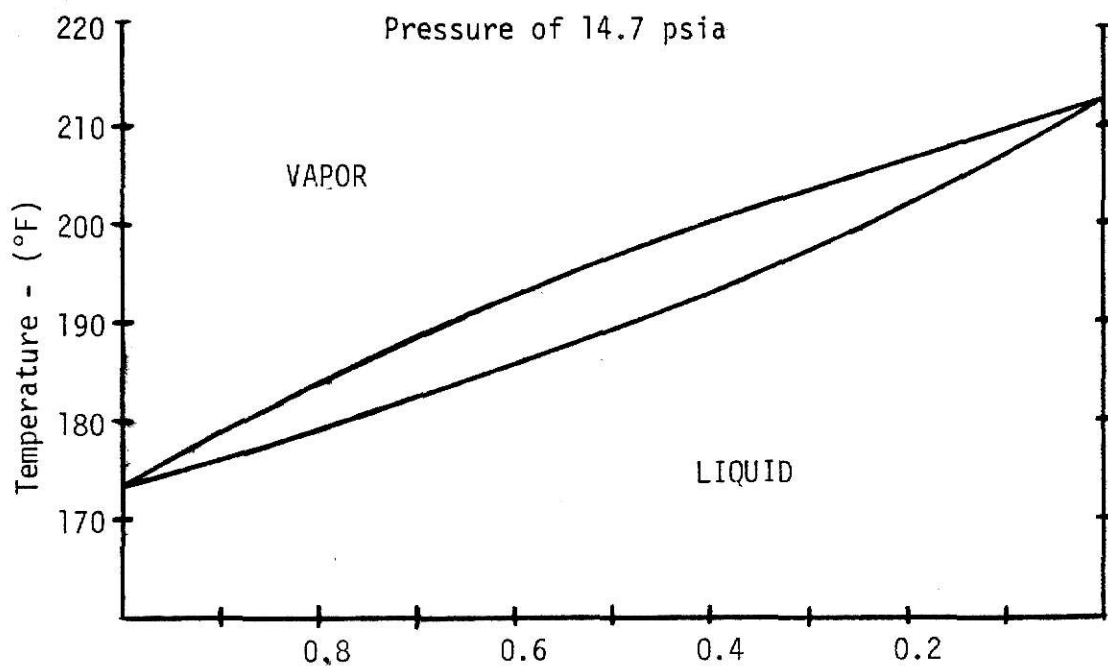
Another possible reason for the difference is the accuracy of computer parameters to the actual flow rates, pressure and temperatures of the physical model. Values used in the computer model are only estimates of those that actually exist in the physical model.

The use of a horizontal tube instead of a vertical column proved to be successful. Without the rotating screens this would not necessarily be true. In the fourth experimental run, the stoppage of rotation of the screens had an effect on the temperature gradient and exit concentration of the distillation tube. This indicates the need for the rotating screens to achieve distillation across the length of the tube.

Completion of the computer model and the physical model fulfilled the objectives set out in the thesis. Even though the computer model was not perfect it did indicate that the distillation system would work. This



Actual Phase Equilibrium Diagram for Ethanol-Water.



Ideal Phase Equilibrium Diagram for Ethanol-Water.

Figure 26. Actual and Ideal phase equilibrium diagram for a ethanol-water binary mixture.

lead to the construction of the physical model which also proved to operate.

EFFICIENCY OF PHYSICAL MODEL

In the fourth experiment, the physical model used approximately 68,300 Btu of work in the form of electricity. Of this work 48,800 Btu's was used by the motor driving the compressor, 8,900 Btu's was used by the motor turning the screens and 10,600 Btu's was used by the heat tape to compensate for heat losses. Each gallon of 172 proof ethanol required 17,200 Btu's of work. The ideal work required to separate a 5 mole percent solution into ethanol is approximately 380 Btu per gallon of ethanol recovered (14). This yields a thermodynamic efficiency of 2 percent.

The mechanical efficiency of the pump is only about 15 percent, which indicates that an increase in pump efficiency would be of benefit to the thermodynamic efficiency. Reduction of heat losses and the amount of work to the motor driving the screens would also benefit.

The minimum amount of heat required for distillation of a 5 mole percent ethanol solution is approximately 12,600 Btu per gallon of ethanol recovered (14). In practice the actual amount of heat required is of the magnitude of 52,000 Btu per gallon of ethanol (15). This increase is due mainly to the degradation in heat and mass transfer that exist in normal distillation processes. Considering that it takes roughly 3 Btu's of heat for 1 Btu of work the work required by the physical model is almost equal to the available work of the heat supplied in practice.

$$\frac{52,000}{3} = 17,300 \frac{\text{Btu}}{\text{gal. ethanol}} \quad \text{vs.} \quad 17,200 \frac{\text{Btu}}{\text{gal. ethanol}}$$

If the heat losses and the work required to drive the compressor and screen rotating motor can be reduced, the use of vapor recompression in the distillation system researched in this thesis shows promise of reducing energy consumption in distillation.

RECOMMENDATIONS

Much further work needs to be undertaken in optimization of the distillation system constructed by the author. This should include optimization of reflux, rotation speed of screens, pump capacity, pump efficiency, heat losses, and operating pressure of the system. The possibility of operating in a higher pressure range should also be investigated. Use of variable flow rates in the pump should be evaluated so that use of alternate means of work, (i.e. windmill, waterfall, etc.), can be compared and evaluated for use in the proposed distillation system. Comparing continuous feed operation to batch boiler operation is an area of consideration that should also be evaluated. Improvement of the equilibrium data in the computer model is needed in order to improve the correlation between the two models.

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APPENDIX A

LIST OF SYMBOLS USED IN COMPUTER MODEL

COMMON BLOCK

Symbol	Description	Units
BLA1	Number of moles liquid ethanol in boiler.	lb-mole
BLW1	Number of moles liquid water in boiler.	lb-mole
CPLA	Specific heat capacity of liquid ethanol.	BTU/lb-mole °F
CPLW	Specific heat capacity of liquid water.	BTU/lb-mole °F
CPVA	Specific heat capacity of ethanol vapor.	BTU/lb-mole °F
CPVW	Specific heat capacity of water vapor.	BTU/lb-mole °F
DA	Density of liquid ethanol.	lb-mole/ft ³
DELA(n)	Change in the number of moles liquid ethanol in liquid portion of node n during delta time (DT).	lb-mole
DELW(n)	Change in the number of moles liquid water in liquid portion of node n during delta time (DT).	lb-mole
DNLA(n)	Number of moles liquid ethanol dropped after equilibrium is achieved with vapor in node n.	lb-mole
DNLW(n)	Number of moles liquid water dropped after equilibrium is achieved with vapor in node n.	lb-mole
DT	Time increment (Delta Time).	hour
DTLQ(n)	Temperature of liquid dropped after equilibrium is achieved with vapor in node n.	°R
DW	Density of liquid water	lb-mole/ft ³
DXA(n)	Mole fraction concentration of liquid ethanol that is returned to liquid portion of node n after equilibrium is achieved with vapor.	-----

Symbol	Description	Units
ENTHLQ	Enthalpy of liquid at equilibrium temperature and liquid phase.	BTU/lb-mole
ENTHP2	Enthalpy of vapor exiting pump.	BTU/lb-mole
HVA	Heat of vaporization for ethanol.	BTU/lb-mole
HVW	Heat of vaporization for water.	BTU/lb-mole
IFNC(I,J)	Control code for subroutine AFNC.	-----
K	Number of nodes in distillation	-----
NLA(n)	Number of moles liquid ethanol in liquid portion of node n exiting the node.	lb-mole
NLAK1	Number of moles liquid ethanol refluxed into distillation tube at node K.	lb-mole
NLW(n)	Number of moles liquid water in liquid portion of node n exiting the node.	lb-mole
NLWK1	Number of moles liquid water refluxed into the distillation tube at node K.	lb-mole
NN	Counter	
NR	Code number of IBM card reader.	
NVA(n)	Number of moles ethanol vapor entering node n.	lb-mole
NVW(n)	Number of moles water vapor entering node n.	lb-mole
NW	Code number of IBM line printer.	-----
P2	Pressure outside the distillation system.	lb/in ²
PST	Operating pressure inside the distillation tube.	lb/in ²
QADDBL	Amount of heat added to boiler.	BTU/hr
QAVAl	Heat available to add to boiler.	BTU/hr
QIN(n)	Amount of heat energy brought into liquid node n with liquid movement during time increment.	Btu

Symbol	Description	Units
QNODEK	Amount of extra heat energy	BTU/hr
QOUT(n)	Amount of heat energy removed in liquid node n with movement of liquid during time increment.	BTU
QSTI(n)	Amount of heat energy stored in liquid node n during time increment.	BTU
STNA(n)	Number of moles liquid ethanol stored in liquid portion of node n.	lb-mole
STNW(n)	Number of moles liquid water stored in liquid portion of node n.	lb-mole
TEMPB	Temperature of the boiler.	°R
TEMPEQ	Phase equilibrium temperature (Boiling temperature) of vapor exiting pump if condensed to a liquid at same concentration.	°R
TEMP2P	Temperature of vapor exiting the pump.	°R
TIME	Time	hr
TLQ(n)	Temperature of liquid node n.	°R
TVP(n)	Temperature of vapor node n.	°R
UNLA(n)	Number of moles liquid ethanol lifted up to mix with vapor in node n.	lb-mole
UNLW(n)	Number of moles liquid water lifted up to mix with vapor in node n.	lb-mole
V	Limiting accuracy used in iteration of exit volume compared to pump volume.	ft ³ /hr
VEXIT	Volume of vapor exiting distillation tube.	ft ³ /hr
VLBOIL	Volume of liquid in boiler.	ft ³
VLIFT	Volume of liquid lifted from liquid node n to vapor node n.	ft ³ /hr
VNL(n)	Volume of liquid portion of node n.	ft ³
VPUMP	Pumping capacity of pump.	ft ³ /hr
WKPUMP	Work input to pump.	BTU/lb-mole

Symbol	Description	Units
XA(n)	Mole fraction concentration of liquid ethanol in node n.	-----
XAB2	Mole fraction concentration of liquid ethanol in boiler.	-----
XFNC(2,I,J)	Tabled equilibrium data were used by Subroutine AFNC.	-----
YA(n)	Mole fraction concentration of ethanol vapor in node n.	-----
<u>MAIN PROGRAM</u>		
ALITER	Total number of liters ethanol recovered.	liters
APROOF	Alcoholic proof (i.e. 200 proof = 100% ethanol by volume).	-----
GAINAL	Rate of ethanol distilled from system during time increment.	lb-mole/hr
HCOMB	Heat of combustion of ethanol.	BTU/lb-mole
KCHECK	Control variable used in controlling of reflux.	-----
K1	Dummy variable.	-----
NCOUNT	Counter used in print statements.	-----
PROOF	Ratio of ethanol to total liquid exiting by volume.	-----
RACOWK	Ratio of heat of combustion in ethanol removed from system to the amount of work supplied to the system.	-----
RAGAIN	Ratio of ethanol removed from system to amount of vapor exiting distillation tube into pump.	-----
RETLQ	Dummy variable, total number of moles refluxed.	lb-mole
RR	Reflux Ratio	-----
SRCOWK	Ratio of total ethanol recovered to total work supplied.	-----

Symbol	Description	Units
SUGAIN	Sum of ethanol gain, total ethanol recovered.	lb-mole
SUMREC	Sum of total number of moles liquid recovered.	lb-mole
SUMREF	Sum of total reflux into distillation tube.	lb-mole
SUWKPU	Sum of work supplied to pump, total work supplied since start-up.	BTU
TLITER	Total number of liters liquid recovered.	liters
TN	Dummy variable, used in determining moles stored in liquid node.	lb-mole
TOTREC	Total solution recovered, ethanol and water.	lb-mole

SUBROUTINE VAPOR

NN	Counter	-----
Q	Dummy variable used in heat balance of combining reflux with liquid lift.	BTU
TEMP	Dummy variable, temperature.	°R
TTT	Dummy variable, temperature of liquid in node K.	°R
ULAK	Dummy variable, moles liquid ethanol lifted in node K.	lb-mole
ULWK	Dummy variable, moles liquid water lifted in node K.	lb-mole
UNLT	Dummy variable, total moles of liquid lifted.	lb-mole
VNT	Dummy variable, total moles vapor.	lb-mole
VNTH	Dummy variable used in iteration algorithm of temperature.	°R
VNTL	Dummy variable used in iteration algorithm of temperature.	°R

SUBROUTINE LIQUID

Symbol	Description	Units
TNE	Total moles exiting liquid node.	lb-mole
STNA1	Dummy variable, storage of ethanol.	lb-mole
STNW1	Dummy variable, storage of water.	lb-mole

SUBROUTINE ACNODE

ACON	Mole fraction ethanol.	-----
II	Counter.	-----
NAT	Total moles ethanol.	lb-mole
NLA1	Number moles liquid ethanol exiting the node.	lb-mole
NLA2	Number moles liquid ethanol entering the node.	lb-mole
NLEQ	Total number moles liquid at equilibrium.	lb-mole
NLW1	Number moles liquid water exiting the node.	lb-mole
NLW2	Number moles liquid water entering the node.	lb-mole
NVA1	Number of moles vapor ethanol entering the node.	lb-mole
NVA2	Number of moles ethanol vapor exiting the node.	lb-mole
NVEQ	Total number of moles vapor at equilibrium.	lb-mole
NVW1	Number of moles water vapor entering the node.	lb-mole
NVW2	Number of moles water vapor exiting the node.	lb-mole
NWT	Total number of moles water in node.	lb-mole
PST	Pressure of system that equilibrium takes place at.	lb/in ²
TEMP	New equilibrium temperature.	°R

Symbol	Description	Units
TH	Dummy variable, high temperature in binomial iteration algorithm.	°R
TL	Dummy variable, low temperature in binomial iteration algorithm.	°R
TLQ2	Temperature of liquid entering the node.	°R
TVP1	Temperature of vapor entering the node.	°R
WCON	Mole fraction water.	-----
XA1	Mole fraction ethanol concentration of vapor entering the node.	-----
YA2	Mole fraction ethanol concentration of liquid entering the node.	-----

SUBROUTINE BOILER

BLA2	Dummy variable, moles liquid ethanol in boiler.	lb-mole
BLW2	Dummy variable, moles liquid water in boiler.	lb-mole
NC	Counter.	-----
TBDUM	Dummy variable, temperature of boiler.	°R
TH	Dummy variable, high temperature in binomial iteration of new boiler temperature.	°R
TL	Dummy variable, low temperature in binomial iteration of new boiler temperature.	°R
XAB2	Dummy variable, ethanol concentration of liquid in boiler.	-----
XADUM2	Mole fraction ethanol concentration in boiler during binomial iteration.	-----

Symbol	Description	Units
CPEXIT	Specific heat of vapor exiting distillation tube and entering pump.	BTU/lb-mole °R
DUMRAK	Dummy variable, ratio $k-1/k$.	-----
NCC	Counter.	-----
RATK	Ratio of specific heats.	-----

APPENDIX B

PROGRAM LISTING OF COMPUTER MODEL

```

C * * * * *
C * * *   COMPUTER MODEL OF A HORIZONTAL DISTILLATION TUBE
C * * *   USING VAPOR RECOMPRESSION IN THE DISTILLATION OF AN
C * * *   ETHANOL AND WATER MIXTURE FROM A BATCH BOILER.
C * * * * *
1000 FORMAT(5I10)
1001 FORMAT(8E10.4)
1500 FORMAT ('0',I6,' * * * * *   VOLUME EXIT = ',E16.6)
4040 FORMAT (I4,9E14.6)
4050 FORMAT ('0 N   UNLA',10X,'UNLW',10X,'DNLA',10X,'DNLW',
  @10X,'QIN',11X,'QOUT',10X,'QSTI',10X,'DELA',10X,'DELW')
4060 FORMAT ('0 MOLES FEEDBACK *** WATER = ',E14.6,' ALC = ',
  @E14.6,' ALC CONCENTRATION = ',F8.4)
5000 FORMAT (I4,9E14.6)
5001 FORMAT ('1')
5002 FORMAT ('0 FINAL RESULTS OF PROGRAM * * * * *')
5003 FORMAT ('0 *****   TIME = ',F8.3)
5004 FORMAT ('0$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$',
  @'$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$',
  @'$$$$$$$$$$$$$$$$$$$$$$$$$$$$')
5005 FORMAT (' N   NVW',11X,'NVA',11X,'ALC CCN VAP',3X,
  @'TEMP VAP',6X,'NLW',11X,'NLA',11X,'ALC CON LIQ',3X,
  @'TEMP LIQ',6X,'VOL OF LIQ')
5006 FORMAT (' ')
6010 FORMAT(6E16.6)
6020 FORMAT ('0ALC CON LIQ BOIL VOL OF LQ BOIL HEAT',1X,
  @'ADD BOIL MOLE LIQ ALC IN BL MOLE LQ WATER ',1X,
  @' TEMP OF BOILER')
7005 FORMAT ('0 * * * RESULTS OF PUMP SUBROUTINE * * *')
7020 FORMAT (6E16.6)
7010 FORMAT ('0 PUMP WORK',6X,'TEMP EXIT PUMP',4X,'TEMP EQUIL'
  @,7X,'ENTH EXIT PUMP',4X,'ENTH LIQUID',6X,'AVAL HEAT')
8000 FORMAT ('0 NET ALC GAIN = ',E14.6,' MOLES * * *',2X,
  @' RATIO OF MOLES ALC RECOVERED TO MOLES TOTAL THROUGH'
  @,1X,'PUMP = ',E14.6)
8005 FORMAT ('0 RATIO OF POSSIBLE HEAT OF COMBUSTION/',1X,
  @'TC WORK USED TO PRODUCE = ',E14.6)
8010 FORMAT ('0 TOTAL MOLES RECOVERED DURING PROCESS = ',
  @E14.6,' MOLES')
8020 FORMAT ('0 * * * * * RATIO OF VOLUME ALC TO TOTAL VOLUME='
  @,E14.6,' ** PROOF = ',F14.3)
8040 FORMAT ('0TOTAL ALC GAIN = ',E14.6,' MOLES ***',E14.6,
  @' LITERS *** TOTAL RECOVERED = ',E14.6,' LITERS')
8050 FORMAT ('0RATIO OF TOTAL ALC HEAT COMBUSTION TO TOTAL ',
  @'WORK SUPPLIED = ',E14.6,' ** TOTAL WORK SUPPLIED TO',
  @' PUMP = ',E14.6,' BTU')
8060 FORMAT ('0 INSTANTANECUS REFLUX RATIO = ',E14.6,
  @' AVERAGE REFLUX RATIO = ',E14.6)
      REAL NVA, NVW, NLA, NLW, NLWK1, NLAK1
      COMMON XFNC(2,10,2), IFNC(2,5), NW, NR, CA, DW, CPLA, CPLW, CPVW,
      @CPVA, HVA, HVW, TIME, NVW(21), NVA(21), UNLW(20), UNLA(20),

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@DNLA(20),DNLW(20),TLQ(20),DTLQ(20),TVP(21),XA(20),
@DXA(20),YA(21),PST,VPUMP,V,STNA(20),STNW(20),NLA(20),
@NLW(20),VLIFT,DT,K,VNL(20),DELA(20),DELW(20),QIN(20),
@QOUT(20),QSTI(20),NN,VEXIT,QADDBL,TEMPB,XAB2,BLW1,
@BLA1,VLBOIL,WKPUMP,TEMP2P,TEMPEQ,ENTHP2,ENTHLQ,QAVAL,P2,
@NLWK1,NLAK1,QNODEK
  NW=6
  NR=5
  READ(NR,1000) ((IFNC(1,I),I=1,5)
  L=IFNC(1,4)
  READ(NR,1001) ((XFNC(1,J,K),K=1,2),J=1,L)
  READ(NR,1000) ((IFNC(2,I),I=1,5)
  L=IFNC(2,4)
  READ(NR,1001) ((XFNC(2,J,K),K=1,2),J=1,L)
C * * * INITIALIZATION OF VALUES FOR THIS PROGRAM
C * * *   K   IS THE NUMBER OF NODES IN THE DISTILLATION TUBE
  K=10
C * * * * *
  HCCMB=530426.0
  DA=1.048
  CW=3.45
  CPLA=29.9
  CPLW=18.0
  CPVA=15.7
  CPVW=8.01
  HVW=18237.
  HVA=16882.
C * * * * *
  NVA(1)=0.0599
  NVW(1)=0.4976
  YA(1)=0.1075
  TVP(1)=610.0
  BLW1=8.25
  BLA1=0.44
  TEMPB=TVP(1)
  DO 2 N=1,K
  XA(N)=0.077
  VNL(N)=0.006
  TN=(VNL(N)*DA*DW)/(DW*XA(N)+DA*(1.0-XA(N)))
  STNA(N)=TN*XA(N)
  STNW(N)=TN*(1.0-XA(N))
2  TLQ(N)=560.0
  VLIFT=0.9
  TLC(K+1)=550.0
  UNLW(K+1)=0.0
  UNLA(K+1)=0.0
  NLA(K+1)=0.0
  NLW(K+1)=0.00
  NLWK1=0.250
  NLAK1=0.056
  XA(K+1)=0.183
  PST=4.0
  P2=14.7
  VPUMP=600.0
  V=10.
  STNA(K+1)=0.0
  STNW(K+1)=0.0
  DT=0.005
C * * * * *
C * * * * *

```

```

SUGAIN=0.0
SUWKPU=0.0
SUMREC=0.0
SUMREC=0.0
TIME=0.0
KCHECK=1
C * * * NCCUNT CONTROLS PRINT STATEMENTS
NCCUNT=50
C * * * THIS IS THE START OF THE MAIN PROGRAM LCCP FOR REAL TIME
DO 8 I=1,3001
IF (I.GE.200) DT=0.02
CALL VAPOR
CALL LIQUID
CALL BOILER
CALL PUMP
TIME=TIME+DT
C * * * CALCULATION OF CONDITIONS AND AMOUNT OF
C * * * LIQUID EXITING THE SYSTEM.
GAINAL=NVA(K+1)-NLAK1
RAGAIN=GAINAL/(NVA(K+1)+NVW(K+1))
TOTREC=NVA(K+1)+NVW(K+1)-NLWK1-NLAK1
RACOWK=(GAINAL*HCCMB)/(WKPUMP*(NVA(K+1)+NVW(K+1)))
PROCF=(NVA(K+1)/CA)/((NVA(K+1)/CA)+(NVW(K+1)/DW))
APROCF=PROCF*200.0
SUGAIN=SUGAIN+(GAINAL*DT)
SUWKPU=SUWKPU+(WKPUMP*(NVA(K+1)+NVW(K+1))*DT)
SRCOWK=(SUGAIN*HCCMB)/SUWKPU
SUMREF=SUMREF+((NLAK1+NLWK1)*DT)
SUMREC=SUMREC+(TOTREC*DT)
RR=(NLAK1+NLWK1)/TOTREC
AVGRR=SUMREF/SUMREC
ALITER=SUGAIN*26.3032
TLITER=SUMREC*26.3032
C * * * START OF THE PRINT STATEMENTS.
IF (NCCUNT.LT.50) GOTO 222
WRITE (6,5001)
WRITE (6,5004)
WRITE (6,5002)
WRITE (6,5003) TIME
WRITE (6,5005)
K1=K+1
DO 5 N=1,K1
5 WRITE (6,5000) N,NVW(N),NVA(N),YA(N),TVP(N),NLW(N),NLA(N)
  @,XA(N),TLQ(N),VNL(N)
  WRITE (6,4050)
  DO 6 N=1,K
  WRITE (6,4040) N,UNLA(N),UNLW(N),DNLA(N),DNLW(N),QIN(N),
  @QOUT(N),QSTI(N),DELA(N),DELW(N)
6 CONTINUE
  WRITE (6,4060) NLWK1,NLAK1,YA(K+1)
  WRITE (6,6020)
  WRITE (6,6010) XAB2,VLBOIL,QADDBL,BLA1,BLW1,TEMPB
  WRITE (6,1500) NN, VEXIT
  WRITE (6,7005)
  WRITE (6,7010)
  WRITE (6,7020) WKPUMP,TEMP2P,TEMPEQ,ENTHP2,ENTHLQ,QAVAL
  WRITE (6,8010) TOTREC
  WRITE (6,8005) RACOWK
  WRITE (6,8000) GAINAL,RAGAIN
  WRITE (6,8020) PROCF,APROCF

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```

WRITE (6,8040) SUGAIN,ALITER,TLITER
WRITE (6,8050) SRCOWK,SUWKPU
WRITE (6,8060) RR,AVGRR
WRITE (6,5004)
WRITE (6,5006)
NCCOUNT=0
222 NCCOUNT=NCCOUNT+1
   XA(K+1)=YA(K+1)
C * * * CONTROL ALGORITHM FOR REFLUX.
   TNO=(NVA(K+1)+NVW(K+1))*1.01
   TNI=NLWK1+NLAK1
   IF(KCHECK.GE.2) GOTO 120
   IF(YA(K+1).GE.0.65) GOTO 110
105 NLWK1=NVW(K+1)
   NLAK1=NVA(K+1)
   GOTO 8
110 KCHECK=2
120 IF (TNI.GT.TNO) GOTO 105
   IF (YA(K+1)-0.65) 140,150,160
140 RETLQ=(NLWK1+NLAK1)*1.005
   NLWK1=RETLQ*(1.0-YA(K+1))
   NLAK1=RETLQ*YA(K+1)
   GOTO 8
150 RETLQ=NLWK1+NLAK1
   NLWK1=RETLQ*(1.0-YA(K+1))
   NLAK1=RETLQ*YA(K+1)
   GOTO 8
160 RETLQ=(NLWK1+NLAK1)*0.995
   NLWK1=RETLQ*(1.0-YA(K+1))
   NLAK1=RETLQ*YA(K+1)
8 CONTINUE
  STOP
  END

```

```

SUBROUTINE VAPOR
  REAL NVA, NVW, NLA, NLW, NLWK1, NLAK1
  COMMON XFNC(2,10,2), IFNC(2,5), NW, NR, CA, DW, CPLA, CPLW, CPVW,
    @CPVA, HVA, HVW, TIME, NVW(21), NVA(21), UNLW(20), UNLA(20),
    @DNLA(20), DNLW(20), TLQ(20), DTLQ(20), TVP(21), XA(20),
    @DXA(20), YA(21), PST, VPUMP, V, STNA(20), STNW(20), NLA(20),
    @NLW(20), VLIFT, DT, K, VNL(20), DELA(20), DELW(20), QIN(20),
    @QOUT(20), QSTI(20), NN, VEXIT, QADDBL, TEMPB, XAB2, BLW1,
    @BLA1, VLBOIL, WKPUMP, TEMP2P, TEMPEQ, ENTHP2, ENTHLQ, QAVL, P2,
    @NLWK1, NLAK1, QNODEK
1000 FORMAT ('ITERATIONS EXCEEDED ON VOLUME CHECK - NODE NO=',I4,
  @' VOLUME EXIT =',E14.6,' TIME =',F7.2)
  DO 5 N=1,K
    UNLT=VLIFT/(DW-(DW-DA)*XA(N))
    UNLA(N)=XA(N)*UNLT
  5 UNLW(N)=(1-XA(N))*UNLT
  NN=0
C * * * THIS STEP MIXES THE REFLUX LINE WITH THE LIQUID PICKED
C * * * UP IN THE LAST NODE, (NODE K)
  TTT=TLQ(K)
  ULAK=UNLA(K)
  ULWK=UNLW(K)
  UNLA(K)=UNLA(K)+NLAK1
  UNLW(K)=UNLW(K)+NLWK1
  C=(ULAK*CPLA+ULWK*CPLW)*TLQ(K)+

```

```

      @{NLAK1*CPLA+NLWK1*CPLW)*TLQ(K+1)
      TLQ(K)=Q/((UNLA(K)*CPLA+UNLW(K)*CPLW)
C * * * * *
      VNT=NVA(1)+NVW(1)
      VNTH=VNT+0.15
      VNTL=VNT-0.15
20  CONTINUE
      VNT=(VNTH+VNTL)/2.0
      NVW(1)=VNT*(1.0-YA(1))
      NVA(1)=VNT*YA(1)
C * * * START OF LOOP CALLING SUBROUTINE ACNODE TO DETERMINE
C * * * EQUILIBRIUM ON EACH VAPOR NODE.
      DO 50 N=1,K
      QNODEK=0.0
      IF(N.EQ.K) QNODEK=0.0
      CALL ACNODE (TEMP,TVP(N),TLQ(N),NVA(N),NVW(N),NVA(N+1),
      @NVW(N+1),DNLW(N),DNLA(N),UNLW(N),UNLA(N),PST,
      @YA(N+1),DXA(N),N)
      DTLQ(N)=TEMP
50  TVP(N+1)=TEMP
      NN=NN+1
C * * * BINOMIAL ITERATION TO DETERMINE THE CORRECT EXIT VOLUME
C * * * DUE TO INITIAL INPUT INTO THE DISTILLATION TUBE.
      VEXIT=(NVA(K+1)+NVW(K+1))*1545.*TEMP/(PST*144.)
      IF (ABS(VEXIT-VPUMP).LE.V) GOTO 90
      IF (NN.GE.15) GO TO 70
      IF (VEXIT-VPUMP) 80,90,60
60  VNTH=VNT
      GO TO 20
80  VNTL=VNT
      GOTO 20
70  WRITE (6,1000) N,VEXIT,TIME
90  TLQ(K)=TTT
      UNLW(K)=ULWK
      UNLA(K)=ULAK
      RETURN
      END

```

SUBROUTINE LIQUID

```

      REAL NVA, NVW, NLA, NLW, NLWK1, NLAK1
      COMMON XFNC(2,10,2), IFNC(2,5), NW, NR, DA, DW, CPLA, CPLW, CPVW,
      @CPVA, HVA, HVW, TIME, NVW(21), NVA(21), UNLW(20), UNLA(20),
      @DNLA(20), DNLW(20), TLQ(20), DTLQ(20), TVP(21), XA(20),
      @DXA(20), YA(21), PST, VPUMP, V, STNA(20), STNW(20), NLA(20),
      @NLW(20), VLIFT, DT, K, VNL(20), DELA(20), DELW(20), QIN(20),
      @QOUT(20), QSTI(20), NN, VEXIT, QADDBL, TEMPB, XAB2, BLW1,
      @BLA1, VLBOIL, WKPUMP, TEMP2P, TEMPEQ, ENTHP2, ENTHLQ, QAVL, P2,
      @NLWK1, NLAK1, QNODEK
      N=K
C * * * VOLUMETRIC BALANCE - CONSTANT LIQUID VOLUME IN EACH NODE
99  XW=1.0-XA(N)
      TNE=(DA*DW/((DA*XW+DW*XA(N)))*((DNLA(N)+NLA(N+1)-UNLA(N))/
      @DA+((DNLW(N)+NLW(N+1)-UNLW(N))/DW)
      NLA(N)=TNE*XA(N)
      NLW(N)=TNE*XW
C * * * MASS BALANCE TO DETERMINE THE NEW CONCENTRATION OF THE
C * * * CONSTANT VOLUME LIQUID NODE.
      STNA1=STNA(N)
      STNW1=STNW(N)

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      DELA(N)=(NLA(N+1)+DNLA(N)-UNLA(N)-NLA(N))*DT
      DELW(N)=(NLW(N+1)+DNLW(N)-UNLW(N)-NLW(N))*DT
      STNA(N)=STNA(N)+DELA(N)
      STNW(N)=STNW(N)+DELW(N)
      VNL(N)=STNA(N)/DA+STNW(N)/DW
C * * * DETERMINATION OF THE NEW MOLE FRACTION ETHANOL
C * * * IN LIQUID NODE.
      XA(N)=STNA(N)/(STNA(N)+STNW(N))
C * * * ENERGY BALANCE - TO DETERMINE THE NEW TEMPERATURE OF
C * * * THE LIQUID NODE.
      QIN(N)=(NLA(N+1)*CPLA+NLW(N+1)*CPLW)*TLQ(N+1)+(DNLA(N)*
      @CPLA+DNLW(N)*CPLW)*DTLQ(N))*DT
      QOUT(N)=(NLA(N)+UNLA(N))*CPLA+(NLW(N)+UNLW(N))*
      @CPLW)*TLQ(N)*DT
      QSTI(N)=(STNA1*CPLA+STNW1*CPLW)*TLQ(N)
      TLC(N)=(QIN(N)+QSTI(N)-QOUT(N))/(STNA(N)*CPLA+STNW(N)*CPLW)
      N=N-1
      IF(N.EQ.0) GOTO 55
      GOTO 99
55 CONTINUE
C WRITE(6,4010)
  K1=K+1
  RETURN
  END

      SUBROUTINE ACNODE(TEMP,TVP1,TLQ2,NVA1,NVW1,NVA2,NVW2,NLW1,
      @NLA1,NLW2,NLA2,PSTD,YA2,XA1,N)
      COMMON XFNC(2,10,2),IFNC(2,5),NW,NR,DA,DW,CPLA,CPLW,CPVW,
      @CPVA,HVA,HVW,TIME,NVW(21),NVA(21),UNLW(20),UNLA(20),
      @DNLA(20),DNLW(20),TLQ(20),DTLQ(20),TVP(21),XA(20),
      @DXA(20),YA(21),PST,VPUMP,V,STNA(20),STNW(20),NLA(20),
      @NLW(20),VLIFT,DT,K,VNL(20),DELA(20),DELW(20),QIN(20),
      @QOUT(20),QSTI(20),NN,VEXIT,QADDBL,TEMPB,XAB2,BLW1,
      @BLA1,VLBOL,WKPUMP,TEMP2P,TEMPEQ,ENTHP2,ENTHLQ,QAVAL,P2,
      @NLWK1,NLAK1,QNODEK
      REAL NLA1,NLA2,NLW1,NLW2,NVA2,NVA1,NVW1,NVW2,
      @NAT,NWT,NVEQ,NLEQ
C * * * THIS SUBROUTINE DETERMINES THE CONCENTRATION AND QUANTITY
C * * * OF ETHANOL AND WATER LEAVING A NODE AS VAPOR AND LIQUID
C * * * AFTER BEING COMBINED AS VAPOR AND LIQUID AT DIFFERENT
C * * * TEMPERATURE AND CONCENTRATIONS.
2002 FORMAT (' NUMBER OF ITERATIONS EXCEEDED IN ACNODE',
      @' SUBPROGRAM. TIME=',F7.2,'NODE =',I4)
2001 FORMAT (' ',I4,5X,8E14.6)
2003 FORMAT (' OITERATION    TEMP',10X,'DELTAH',10X,'NVA2',
      @10X,'NVW2',10X,'NLA1',10X,'NLW1',10X,'PSA',11X,'PSW')
2004 FORMAT (' ')
      II=0
      TH=TVP1+10.0
      TL=TLQ2-15.0
650 TEMP=(TL+TH)/2.0
600 CONTINUE
C * * * SUBROUTINE AFNC IS CALLED TO DETERMINE A VALUE FOR
C * * * THE VAPOR PRESSURES OF ETHANOL AND WATER AT THE
C * * * TEMPERATURE, (TEMP).
700 CALL AFNC(TEMP,PSA,1)
      CALL AFNC(TEMP,PSW,2)
C * * * CALCULATION OF THE NEW COMPOSITION OF THE NODE
C * * * AFTER EQUILIBRIUM IS ACHIEVED.

```

```

XA1=(PST-PSW)/(PSA-PSW)
IF(XA1.LE.0.0)GO TO 720
IF(XA1.GE.1.0)GO TO 730
XW1=1.0-XA1
YA2=XA1*PSA/PST
YW2=1.0-YA2
C * * * CALCULATION OF THE TOTAL NUMBER OF MOLES ENTERING THE NODE.
NAT=NVA1+NLA2
NWT=NW1+NLW2
C * * * CHECK TO SEE IF THE LIQUID AND VAPOR ARE AT TWO PHASE.
WCON=NWT/(NAT+NWT)
ACON=NAT/(NAT+NWT)
IF(YA2.LE.ACON)GO TO 720
IF(XW1.LE.WCON)GO TO 730
C * * * CALCULATION OF THE NUMBER OF MOLES IN LIQUID AND
C * * * VAPOR STATES AFTER EQUILIBRIUM IS ACHIEVED.
NVEQ=(NAT/XA1-NWT/XW1)/(YA2/XA1-YW2/XW1)
NLEQ=(NAT-NVEQ*YA2)/XA1
C * * * CALCULATION OF THE NUMBER OF MOLES LIQUID AND VAPOR
C * * * OF EACH COMPONENT LEAVING THE NODE AFTER
C * * * EQUILIBRIUM IS ACHIEVED.
NLA1=NLEQ*XA1
NLW1=NLEQ*XW1
NVA2=NVEQ*YA2
NVW2=NVEQ*YW2
GO TO 740
720 NVA2=NLA2+NVA1
NVW2=NLW2+NVW1
NLA1=0.0
NLW1=0.0
GO TO 740
730 NLW1=NLW2+NVW1
NLA1=NLA2+NVA1
NVA2=0.0
NVW2=0.0
GO TO 740
C * * * CALCULATION OF THE ENERGY BALANCE ON THE FLOWS ENTERING
C * * * AND LEAVING THE NODE. IF DELTAH EQUALS ZERO THE
C * * * CORRECT TEMPERATURE, (TEMP), HAS BEEN DETERMINED.
740 DELTAH=(CPVA*TVPI+HVA)*NVA1+(CPVW*TVPI+HVV)*NVW1
      @+(CPLA*NLA2+CPLW*NLW2)*TLQ2-((CPVA*TEMP+HVA)*NVA2+
      @ (CPVW*TEMP+HVV)*NVW2+(CPLA*NLA1+CPLW*NLW1)*TEMP)+QNODEK
C * * * TEST TO DETERMINE IF THE TEMPERATURE, (TEMP), IS TO
C * * * HIGH OR LOW IN THE BINOMIAL ITERATION TECHNIQUE.
      II=II+1
C * * * BINOMIAL ITERATION TECHNIQUE--- DIVIDE IN HALF EACH TRY.
      IF (II.GE.35) GOTO 840
      IF (ABS(DELTAH/(NVA2+NVW2+NLA1+NLW1)).LE.5.00) GOTO 850
      IF (DELTAH) 750,850,950
750 TH=TEMP
      GO TO 650
950 TL=TEMP
      GO TO 650
840 WRITE(6,2002) TIME,N
      WRITE (6,2003)
      WRITE(6,2004)
      WRITE(6,2001) II,TEMP,DELTAH,NVA2,NVW2,NLA1,NLW1,PSA,PSW
850 RETURN
      END

```



```

      SUBROUTINE BOILER
C * * * THIS SUBROUTINE DETERMINES THE NEW CONCENTRATION IN
C * * * THE BOILER AND THE HEAT ADDED TO THE BOILER
C * * * FOR VAPORIZATION.
      REAL NVA, NVW, NLA, NLW, NLWK1, NLAK1
      COMMON XFNC(2,10,2), IFNC(2,5), NW, NR, DA, DW, CPLA, CPLW, CPVW,
      @CPVA, HVA, HVW, TIME, NVW(21), NVA(21), UNLW(20), UNLA(20),
      @DNLA(20), DNLW(20), TLQ(20), DTLQ(20), TVP(21), XA(20),
      @DXA(20), YA(21), PST, VPUMP, V, STNA(20), STNW(20), NLA(20),
      @NLW(20), VLIFT, DT, K, VNL(20), DELA(20), DELW(20), QIN(20),
      @QOUT(20), QSTI(20), NN, VEXIT, QADDBL, TEMPB, XAB2, BLW1,
      @BLA1, VLBOIL, WKPUMP, TEMP2P, TEMPEQ, ENTHP2, ENTHLQ, QAVAIL, P2,
      @NLWK1, NLAK1, QNODEK
6000 FORMAT (' ERROR IN NUMBER OF ITERATIONS TO SOLVE ',
      @' EQUILIBRUM IN BOILER')
      NC=0
      TBDUM=TEMPB
C * * * DETERMINATION OF THE AMOUNT OF ETHANOL
C * * * AND WATER IN BOILER.
      BLA2=BLA1+(NLA(1)-NVA(1))*DT
      BLW2=BLW1+(NLW(1)-NVW(1))*DT
      XAB2=BLA2/(BLA2+BLW2)
C * * * BINOMIAL ITERATION TO DETERMINE REQUIRED
C * * * BOILER TEMPERATURE.
      TH=TEMPB+2.0
      TL=TEMPB-2.0
88 TEMPB=(TH+TL)/2.0
      NC=NC+1
      CALL AFNC(TEMPB, PSA, 1)
      CALL AFNC(TEMPB, PSW, 2)
      XADUM2=(PST-PSW)/(PSA-PSW)
      IF (ABS(XADUM2-XAB2).LE.0.001) GOTO 10
      IF (NC.GE.15) GOTO 99
      IF (XADUM2-XAB2) 5,10,15
5 TH=TEMPB
      GOTO 88
15 TL=TEMPB
      GOTO 88
99 WRITE (6,6000)
      GOTO 22
10 CCNTINUE
      TVP(1)=TEMPB
      YA(1)=XAB2*PSA/PST
C * * * HEAT BALANCE ON THE BOILER.
      QINB=(NLA(1)*CPLA+NLW(1)*CPLW)*TLQ(1)*DT
      QOUTB=(NVA(1)*(CPVA*TVP(1)+HVA)+NVW(1)*(CPVW*
      @TVP(1)+HVW))*DT
      QSTB1=(BLA1*CPLA+BLW1*CPLW)*TBDUM
      QSTB2=(BLA2*CPLA+BLW2*CPLW)*TEMPB
      QADDBL=(QSTB2-QSTB1+QOUTB-QINB)/DT
      VLBOIL=BLW2/DW+BLA2/DA
      BLA1=BLA2
      BLW1=BLW2
22 CCNTINUE
      RETURN
      END

```

SUBROUTINE PUMP

```

C * * * THIS SUBROUTINE DETERMINES THE PROPERTIES OF THE VAPOR
C * * * EXITING THE PUMP.
      REAL NVA, NVW, NLA, NLW, NLWK1, NLAK1
      COMMON XFNC(2,10,2), IFNC(2,5), NW, NR, DA, DW, CPLA, CPLW, CPVW,
      @CPVA, HVA, HVW, TIME, NVW(21), NVA(21), UNLW(20), UNLA(20),
      @DNLA(20), DNLW(20), TLQ(20), DTLQ(20), TVP(21), XA(20),
      @DXA(20), YA(21), PST, VPUMP, V, STNA(20), STNW(20), NLA(20),
      @NLW(20), VLIFT, DT, K, VNL(20), DELA(20), DELW(20), QIN(20),
      @QOUT(20), QSTI(20), NN, VEXIT, QADDBL, TEMPB, XAB2, BLW1,
      @BLA1, VLBOIL, WKPUMP, TEMP2P, TEMPEQ, ENTHP2, ENTHLQ, QAVAIL, P2,
      @NLWK1, NLAK1, QNODEK
      7000 FORMAT ('0 ITERATIONS EXCEEDED IN PUMP SUBROUTINE WHILE',
      @' SOLVING FOR NEW EQUILIBRIUM TEMPERATURE')
C * * * DETERMINATION OF THE SPECIFIC HEAT
C * * * CAPACITY OF THE VAPOR.
      CPEXIT=(NVA(K+1)*CPVA+NVW(K+1)*CPVW)/(NVA(K+1)+NVW(K+1))
      RATK=CPEXIT/(CPEXIT-1.9859)
      DUMRAK=(RATK-1.0)/RATK
C * * * CALCULATION OF PUMP WORK AND THE EXITING TEMPERATURE.
      WKPUMP=((P2/PST)**DUMRAK-1.0)*((1545.4*TVP(K+1))/
      @{DUMRAK*778.0)
      TEMP2P=TVP(K+1)*((P2/PST)**DUMRAK)
      NCC=0
      TH=674.0
      TL=TVP(K+1)
C * * * BINOMIAL ITERATION TO DETERMINE THE EQUILIBRIUM,
C * * * (BOILING), TEMPERATURE OF VAPOR EXITING THE PUMP.
      88 TEMP=(TH+TL)/2.0
      NCC=NCC+1
      CALL AFNC(TEMP, PSA, 1)
      CALL AFNC(TEMP, PSW, 2)
      XADUMP=(P2-PSW)/(PSA-PSW)
      IF (ABS(XADUMP-YA(K+1)).LE.0.005) GOTO 10
      IF (NCC.GE.15) GOTO 99
      IF (XADUMP-YA(K+1)).5, 10, 15
      5 TH=TEMP
      GOTO 88
      15 TL=TEMP
      GOTO 88
      99 WRITE (6,7000)
      GOTO 22
      10 CONTINUE
      TEMPEQ=TEMP
C * * * DETERMINATION OF THE ENTHALPY DIFFERENCE BETWEEN
C * * * VAPOR EXITING THE PUMP AND VAPOR CONDENSED TO A
C * * * LIQUID AT ITS EQUILIBRIUM TEMPERATURE.
      ENTHP2=TEMP*(CPLA*NVA(K+1)+CPLW*NVW(K+1))+NVA(K+1)*HVA+
      @NVW(K+1)*HVW+(TEMP2P-TEMP)*(CPVA*NVA(K+1)+CPVW*NVW(K+1))
      ENTHLQ=TEMP*(CPLA*NVA(K+1)+CPLW*NVW(K+1))
      QAVAIL=ENTHP2-ENTHLQ
      22 CONTINUE
      RETURN
      END

```

SUBROUTINE AFNC(XZ,Y,IZ)

```

C ***** SUBROUTINE AFNC -- FURNISHED BY DR. B W JONES
      COMMON XFNC(2,10,2), IFNC(2,5), NW, NR
C *****
C REASSIGN THE INPUT ARGUMENTS

```



```

      X=XZ
      I=IZ
C   THIS IS A SUBROUTINE WHICH INTERPOLATES BETWEEN TABLED FUN-
C   CTION VALUES BY FITTING A POLYNOMIAL TO A NUMBER OF POINTS.
C   X IS THE VALUE OF THE INDEPENDENT VARIABLE
C   Y IS THE VALUE OF THE DEPENDENT VARIABLE CALCULATED
C   I IS THE FUNCTION NUMBER
C   THE USER MUST SUPPLY A COMMON STATEMENT SUITABLE FOR THE
C   FUNCTIONS BEING USED
C   TWO ARRAYS MUST BE SUPPLIED TO IT THROUGH COMMON
C   XFNC(I,J,K) IS THE ARRAY WHICH CONTAINS THE TABLED FUNCTION
C   I IS THE NUMBER OF THE FUNCTION BEING USED
C   J IS THE INDEX FOR FUNCTION POINTS
C   K IS 1 FOR THE INDEPENDENT VARIABLE AND 2 FOR
C   THE DEPENDENT VARIABLE
C   IFNC(I,J) DESCRIBES THE NATURE OF THE FUNCTION
C   I IS THE NUMBER OF THE FUNCTION
C   THE J VALUES ARE USED TO CONVEY INFORMATION
C   ABOUT THE FUNCTION
C   1 STANDS FOR YES, 0 STANDS FOR NO
C   J=1---EXTEND FUNCTION BELOW MINIMUM VALUE OF
C   INDEPENDENT VARIABLE
C   J=2---EXTEND FUNCTION BEYOND MAXIMUM VALUE
C   OF INDEPENDENT VARIABLE
C   J=3---EQUALLY SPACED VALUES OF INDEPENDENT VARIABLE
C   J=4---IS USED FOR THE NUMBER OF DATA POINTS IN THE FUNCTION
C   J=5---IS USED FOR THE NUMBER OF DATA POINTS
C   TO BE USED IN THE INTERPOLATE
C   IERROR IS A SIGNAL USED TO INDICATE A MALFUNCTION
C   IN THE INTERPOLATION
C   0 INDICATES NO ERRORS. 1 INDICATES AN ERROR
C   NW IS THE PRINTER NUMBER FOR ERROR MESSAGES
C
C
C   REASSIGN OFTEN USED ARRAY VALUES
      J4=IFNC(I,4)
      J5=IFNC(I,5)
      X1=XFNC(I,1,1)
      XN=XFNC(I,J4,1)
C   INITIALIZE ERROR PARAMETER
      IERROR=0
C   CHECK TO SEE IF X IS IN THE PROPER RANGE
      IF(X.GE.X1) GO TO 103
      IF(IFNC(I,1).EQ.1) GO TO 102
      WRITE(NW,101) I,X
101  FORMAT(24H BELOW RANGE OF FUNCTION,I4,G15.4)
      IERROR=1
102  Y=XFNC(I,1,2)
      RETURN
103  IF(X.LE.XN) GO TO 106
      IF(IFNC(I,2).EQ.1) GO TO 105
      WRITE(NW,104) I,X
104  FORMAT(24H ABOVE RANGE OF FUNCTION,I4,G15.4)
      IERROR=1
105  Y=XFNC(I,J4,2)
      RETURN
C   FIND STARTING POINT FOR SEARCH FOR INDEPENDENT
C   VARIABLE INDEXES
106  IX=IFIX(((X-X1)/(XN-X1))*FLOAT(J4-1))+1
      IF(IX.EQ.J4) IX=J4-1

```

```

C ARE VALUES OF INDEPENDENT VARIABLE EQUALLY SPACED
  IF(IFNC(I,3).EQ.0) GO TO 110
C ARE AN EVEN OR ODD NUMBER OF DATA POINTS TO BE USED
1065 A=FLGAT(J5)*.5
  IA=IFIX(A+.1)
  IF(A.GT.FLOAT(IA)) GO TO 107
  IX=IX-IA+1
  GO TO 150
C WHICH PART OF INTERVAL IS POINT IN
107 J=0
  XII=XFNC(I,IX+1,1)
  IF((XII-X)/(XII-XFNC(I,IX,1)).LT.0.5) J=1
  IX=IX-IA+J
  GO TO 150
C SEARCH FOR INDEXES
110 J=0
  K=0
111 IF(X-XFNC(I,IX,1)) 120,120,125
120 IF(J.EQ.0) GO TO 121
  IX=IX-1
  GO TO 1065
121 K=1
  IX=IX-1
  IF(IX.NE.0) GO TO 111
  IX=1
  GO TO 1065
125 IF(K.EQ.1) GO TO 1065
  J=1
  IX=IX+1
  GO TO 111
C SET INDEXES FOR INTERPOLATION
150 IF(IX.LT.1) IX=1
  J=J4-J5+1
  IF(IX.GT.J) IX=J
  L=IX+J5-1
C MAKE INTERPOLATION
  Y=0.
  DO 400 K=IX,L
  YL=1.0
  DO 300 J=IX,L
  IF(J.EQ.K) GO TO 300
  XJ=XFNC(I,J,1)
  YL=YL*(X-XJ)/(XFNC(I,K,1)-XJ)
300 CONTINUE
400 Y=Y+YL*XFNC(I,K,2)
  RETURN
  END

```

C * * * THIS IS THE EQUILIBRIUM DATA USED IN THE COMPUTER MODEL.

540.	1.3	555.	1.9	570.	3.1	585.	4.5
600.	6.6	615.	9.5	630.	13.7	645.	18.7
660.	25.1	675.	33.3				
					10		3
540.	0.5	555.	0.8	570.	1.3	585.	1.95
600.	2.9	615.	4.2	630.	6.0	645.	8.4
660.	11.5	675.	15.5				

ACKNOWLEDGMENT

I wish to thank Dr. Byron Jones for the initial idea of this thesis and for all his guidance and support throughout the research. Also, I would like to thank Professor Robert Crank and Dr. Donald Lenhert for serving on my committee. Thanks also goes to Tom Shrimplin and Gary Thornton for their assistance in construction of the physical model.

I would like to thank Dr. Paul Miller and the Department of Mechanical Engineering for providing financial support during my endeavor as a graduate student at Kansas State University. And, I would like to thank my parents for their support and encouragement throughout my education.

VITA

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DISTILLATION OF AN ETHANOL-WATER BINARY
MIXTURE IN A HORIZONTAL DISTILLATION
TUBE UTILIZING VAPOR RECOMPRESSION

by

KENNETH W. LASSMAN

B.S., Kansas State University, 1980

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the
requirement for the degree

MASTER OF SCIENCE

Department of Mechanical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1982

ABSTRACT

The purpose of this thesis was to evaluate and determine whether the distillation system presented would work. This distillation system involved a horizontal distillation tube in which the process of enriching an ethanol-water binary mixture, of low concentration ethanol to high concentration ethanol, took place. Included in the distillation tube was a rotating screen mechanism which was responsible for the distillation process. Also, incorporated into the system was the process of vapor-recompression. The heat energy required for distillation was supplied by the condensation of vapors in the boiler heat exchanger that were removed from the distillation tube and compressed by a vacuum pump. Operating pressure of the distillation tube was between 2 and 6 psia. The vapors in the boiler heat exchanger were compressed to atmospheric pressure.

Proof of the ability of the distillation system to operate was achieved in a two phase operation. First, an analytic model of the system was developed and written using a computer program. Results of the computer model indicated the proposed distillation system would operate. The second phase of research was the design and construction of a small scale working model. This working model was built by the author and then operated for several experimental runs. Results of the experiments gave further evidence that the proposed distillation system would operate. The efficiency of the model compared favorably with standard distillation systems. Further work in optimizing the proposed distillation system should result in an increase in efficiency over present distillation systems.