MODELLING AND CONTROL PROBLEMS OF DISTILLATION COLUMN

by

M. Noman JAFRI, B.Sc. (Hons) Eng.

A thesis submitted to the Faculty of Science
in partial fulfilment of the requirements for the degree of
Master of Science.

Department of Electrical Engineering,
Faculty of Pure and Applied Science,
The University of Ottawa,
Ottawa, Canada.

1964

Approved for the Department of
Electrical Engineering

Supervisor

Chairman of the Examination
Committee

Chairman of the Department

ABSTRACT

A linearised dynamic model of a 10-plate binary distillation column was obtained by perturbation technique.

The control of the column was considered by two methods: one manipulated variable (reflux) control and two manipulated variables (reflux and reboil) control. These methods were studied on an analog computer. In both cases optimal parameters of the controllers were obtained by integral of the square error criterion for disturbances in the feed composition. The effect of interaction in two manipulated variable control was also studied. It was concluded that two manipulated variable control was practical since it ensures reliability in the operation of the column.

ACKNOWLEDGEMENTS

The author expresses his profound gratitude to Professor G. S. Glinski, who suggested and supervised this project.

The author also thanks:

Dr. B. C. -Y. Lu for providing facilities
to carry out experiment in his Department
of Chemical Engineering,
Miss O. Boshko for assistance in the
evaluation of the data on the digital computer,
Dr. R. K. Wood for useful suggestions.

The author would like also to acknowledge the financial assistance for graduate studies in Canada from the Colombo Plan of Canada and the Atomic Energy Commission of Pakistan.

TABLE OF CONTENTS

Page

Chapter III

Chapter IV

Chapter V

Appendix I

Appendix II

Appendix III

CHAPTER I

i) Introduction

The growing demand for products and human endeavor to achieve the target at the minimum cost, labor and time, introduced the use of machine. In view of man's incapability for quick and accurate adjustment, automatic control of machine was considered necessary and units called "controllers" were invented to replace manual supervision. Process control engineering is the design and study of such controller systems as shown in Fig. 1.1.

In open loop control systems, actual output may be different from the desired output if the components of the system are sensitive to environmental changes such as temperature, humidity, etc. To overcome this drawback of open loop systems, the concept of feedback as shown in Fig. 1.2 was introduced. In this type of system, error signal is obtained from the comparison of actual output and the desired output. Such a system automatically attempts to bring the actual output to the desired level and in this way corrects the difference between the two. In addition, proper feedback tends to linearize the system and minimizes the effects of time constants, which makes the system faster and smoother. The only disadvantage of the feedback, is the possibility of the system becoming unstable.

ii) Process Identification

Transfer Functions:

By definition, the system transfer function is a linear system concept. Physical systems are always nonlinear to some extent depending on their components. Therefore, transfer functions are obtained by linearizing the system for certain range, beyond which the system characteristics change and a new transfer function will be required.

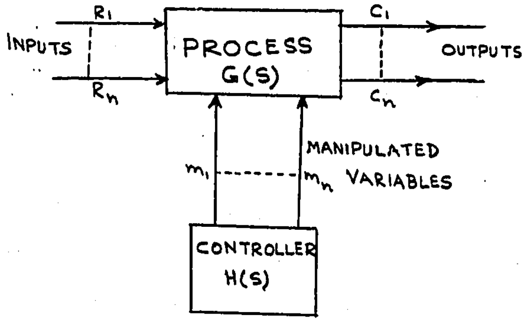


Fig. 1.1. Control System

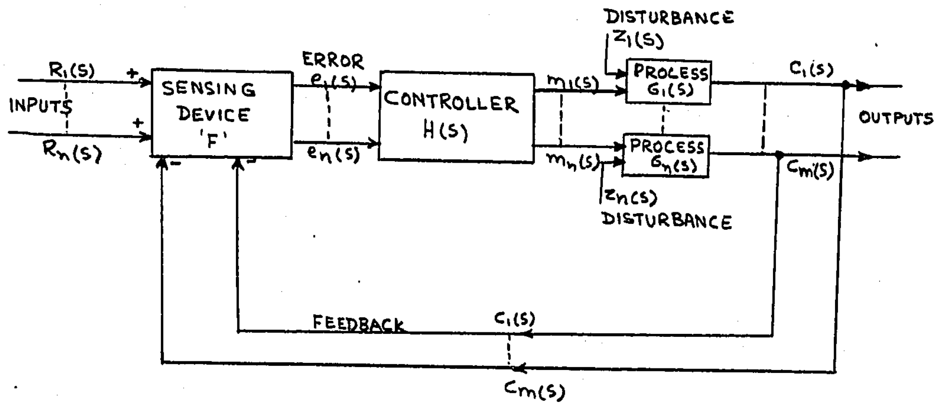


Fig. 1.2. Feedback Control System

The system transfer function is obtained either analytically from the physics of the system and from the manufacturer's data or, experimentally, or by a combination of these two methods. Since in automatic control, dynamics of the system is involved, the experimental technique for the identification of the transfer function is the only practical method. Prior to the application of this technique, the following factors must be examined.

1) Whether the normal signals in the system are sufficient for the determination of the transfer function or some external test signal is required; in the latter case what should be the form and magnitude of the signal?

2) Whether the stored energy in the system is to be considered or ignored, or a method could be devised, which is independent of stored energy?

The difficulty in the process identification depends upon the extent of nonlinearity in the system. If the system is highly nonlinear, then it should be linearized around the operating point. In that case, the amplitude of the test signal should be chosen with great care as with a large amplitude of the disturbing signal, the system could become nonlinear and even unstable. The following methods are commonly used in the process identification.

a) Frequency Response Method:

This technique involves the measurement of gain and phase characteristics of the system as a function of frequency. The test signal is injected when the system has attained steady state condition. The frequency of the test signal is varied and the output in the form of gain and phase is recorded. The steady state transfer function of the system, then in general, may be written as:

$$T(jw) = \frac{C}{R}(jw) \qquad 1.1$$

where

$C(jw)$ is the output of the system.

$R(jw)$ is the input to the system.

The magnitude of the input signal is also varied to check the behaviour of the system at different input levels. This technique requires a large number of tests. Also, it is slow and time consuming, but the accuracy with which it determines the process transfer function justifies its use in a great number of cases.

b) Impulse Response Method:

This technique determines the system characteristics in time domain. Step response, which is the integral of the impulse response is sometimes more suitable in practice. Impulse response can be measured experimentally in any of the following three ways.
1) Exciting the system with an impulse and measuring the response, 2) applying a random signal to the process and measuring the impulse response, 3) exciting the system with any input signal $r(t)$, starting at $t = 0$ and measuring response $c(t)$. If the system has no stored energy at $t = 0$, then the impulse response can be represented by the convolution integral.

$$c(t) = \int_0^t g(x)\,r(t-x)\,dx.$$

A description of these methods can be found in literature [1, 2]. In general, after the data of impulse or step response is obtained, the transfer function can be determined graphically. When the approximate shape of the curve is known, the identification of the transfer function can be obtained accurately by either the digital or the analog computer.

This technique is simple and fast as compared to frequency response method, hence it is more economical. However, the errors in the measurement of the transient response effect the transfer function more than the errors of frequency response. Also, repeated impulse responses are used to average out the effect of noise, whereas noise has no significant effect on the measurement of frequency response method. The choice between frequency and the impulse response methods depends upon several considerations, such as the nature of the test, availability of the equipment and the factor of time.

The identification of a process can also be carried out by the so called "hill-climbing" technique. This technique involves the comparison of the outputs of the process and a model for the same input. The resulting error is used to drive the model parameters to their correct values.

Once the transfer function of the process is determined, the process along with its accessories can be instrumented on an analog computer for synthesis. Prior to the discussion regarding the determination of the transfer function of the controller, some discussion on the optimal control and the performance criteria seems appropriate. In general, the performance criterion is the deciding factor in the determination of the controller transfer function.

iii) Optimal Control

An optimal control of a process is defined as one which drives the process towards optimum with respect to a certain performance criterion. The following steps are essential for this approach.

i) Choice of a suitable performance criterion.
ii) Identification of the current value of the performance criterion.
iii) Comparison with recent test value of performance criterion.

iv) Decision to move to a state, where a better value of the performance criterion may be expected.

v) Repetition of the cycle of the above operations.

The major part of this discussion will be centred around steps i). Steps (ii-v) will be considered when hill-climbing will be discussed in section (v-b) of this chapter.

iv) Choice of a Suitable Performance Criterion

Performance Criterion:

A system is required to perform a certain function in a certain environment and the measure of how well this function is performed is called the "performance criterion".

The criterion used to define an optimum design will depend upon the application of the system being considered. For example, the cost of the power produced could be the criterion on which a power plant design should be optimized for an electric utility application, whereas weight would be more important criterion for optimizing the design of an aircraft system. In a formal mathematical language, the performance criterion 'P' may be defined as

$$P = f_o(x_1, \ldots\ldots, x_n)$$

Subjects to the constraints

$$f_i(x_1, \ldots\ldots, x_n) \geqslant 0 \qquad i = 1, \ldots\ldots m.$$

where xi's are the system variables, which influence its performance.

In general, the following factors influence the choice of the performance criterion.

- i) The output may be a function of more than one variable.
- ii) The effects of interaction among the controlled variables may be such as to decrease the efficiency of the original change.
- iii) More than one objective may be involved.
- iv) The number of possible courses of action can be very large.

The selection of the proper performance criterion should, therefore, take all these conditions into consideration.

After this brief introduction to the idea of performance criterion, its choice for the optimal control of follow up, regulators, end-point and batch-process control is considered.

SERVOMECHANISMS:

These are tracking devices, which must slavishly follow an input signal, usually with power amplification and at a distance and often in the presence of unmeasurable and uncontrollable disturbances as shown in Fig. 1.3. Familiar examples are radar gun aiming, power steering of land, sea and space vehicles, control valve actuations, etc. For such devices, a satisfactory dynamic response depends on the performance criterion used. Servomechanism is made adaptive by the introduction of a regulator loop to maintain a constant optimum performance criterion. Here, "adaptive" is used in the sense of optimal. This ambiguity is quite common in literature. Fig. 1.4 shows one such scheme for adaptive control.

REGULATORS:

These are the devices, which are required to maintain a constant output in the presence of disturbances as given in Fig. 1.3.

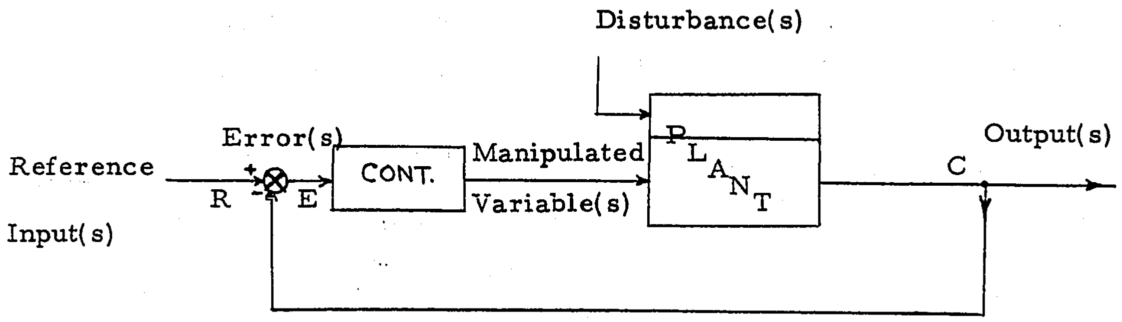


Fig. 1.3. Basic Closed Loop System for Servomechanism or Regulator

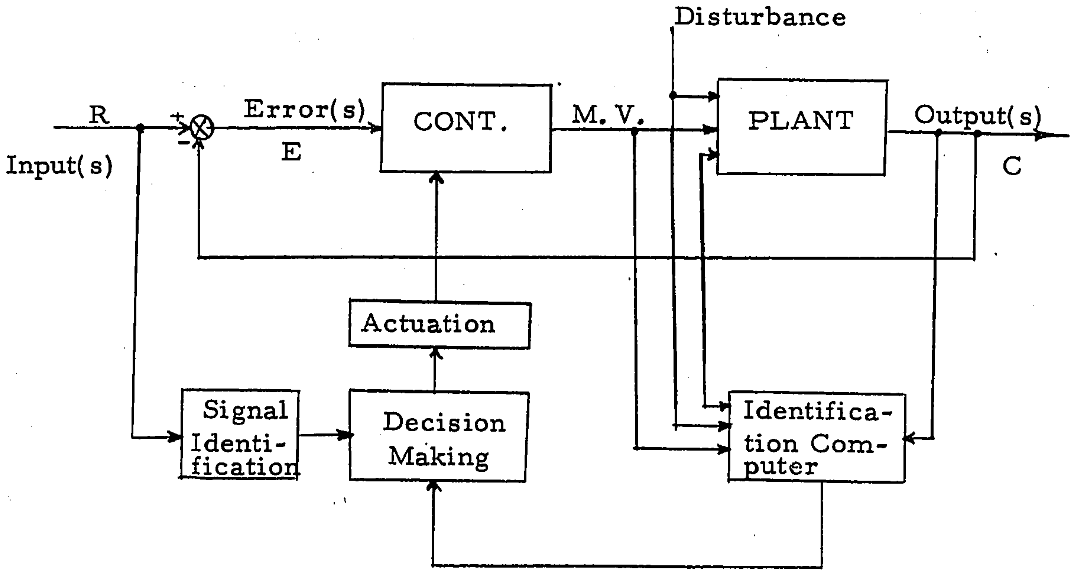


Fig. 1.4. Adaptive Control Configuration

Familiar examples are pressure, temperature, voltage, etc. and disturbances may be the volume flow rate, heat flow rate, current, etc.

In regulating systems and process control the performance criterion should, therefore, be either error or some function of the error or a function of several such variables, which influence the output. For the maximum output, the system should always be operating at the optimum value of the performance criterion. However, in the presence of disturbances and parameter changes, this optimum value of the performance index will generally drift. The process of tracking this optimal value of the performance criterion is that of optimization.

END-POINT AND BATCH PROCESS CONTROL:

In the end-point or batch process control, zero error in the end-point condition is more important than the energy consumption. Therefore, the performance criterion should be a function of end-point conditions.

PROPERTIES OF THE PERFORMANCE CRITERION:

The performance criterion should have the following attributes[3]:

1) Selectivity: that is, the extremum value of the performance criterion should be sharp enough so as to clearly define the optimum controller parameters.
2) Ready Applicability: The performance criterion should be such that it could be handled conveniently either analytically or on an analog or digital computer.

DYNAMIC PERFORMANCE CRITERION:

In the early development of the servomechanism theory, the design was based mainly on trade-off between stability and sufficient speed of response. The optimum conditions, then, were obtained by solving the three term controller or using compensation. Some of the common performance measures are given in Table I. a. Some of these measures are shown on the transient response curve for a step input to a third order system, as in Fig. 1. 5.

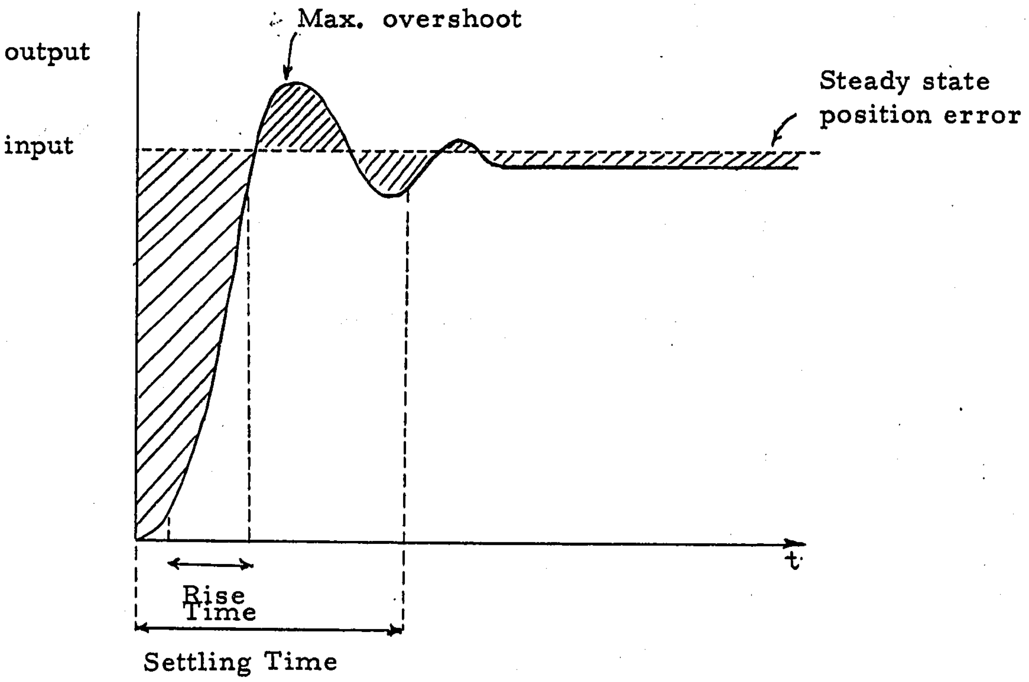


Fig. 1. 5. Transient Response of a 3rd Order System with Proportional Control.

The shaded area in the response curve is contributed by rise time, overshoot, settling time and steady state error and is the measure of the imperfection in the system performance. Therefore, the minimization of this area will obviously bring the system to the optimum. With the development of the control theory, greater interest was focussed on impulse or step response, wherefrom it was realized that error was the measure of imperfection in a system and it should be as near to zero as possible in the transient as well steady state conditions. Thus a performance measure, which is a function of error can be used as a criterion for the optimization of the system. Some of these measures are enlisted in Table I. b. These measures are reliable, as they relate error, which is the measure of imperfection of a system. The relative selectivity of these measures is shown in Fig. 1. 6. Regarding the ready applicability, these measures can easily be instrumented on an analog computer.

Table I: Dynamic Performance Criteria

a) Simple Dynamic Measures.

i) Natural Frequency.
ii) Damping Ratio.
iii) Bandwidth.
iv) Phase Margin.
v) Gain Margin.
vi) Rise Time.
vii) Maximum Overshoot.
viii) Settling Time.
ix) Steady State Error, Position, Velocity.

b) Integrated Transient Measures.

i) Integral square error, I.S.E.[4] $\int_0^\infty [e(t)]^2 \, dt.$

ii) Integral error (control area)[5, 6, 7, 8] C.A. $\int_0^\infty e(t)\, dt.$

iii) Integral time multiplied error,[9] ITE $\int_0^\infty t\, e(t)\, dt.$

iv) Integral absolute error[10, 11], IAE $\int_0^\infty |e(t)|\, dt.$

v) Integral time multiplied absolute error ITAE[3] $\int_0^\infty t\, |e(t)|\, dt.$

vi) Impulse response are ratio IRAR[12] $-\frac{A+}{A-}$

c) Average Statistical Measure.

Mean Square error MSE[13] $\lim_{T\to\infty} \left[\frac{1}{2T} \int_{-T}^{T} [e(t)]^2 \, dt \right]$

This section may be concluded with the remark that integral time multiplied absolute error criterion is more selective and does not penalize instantaneous errors, and it results in a satisfactorily damped system.

In case of regulators, as mentioned earlier, performance criterion is either error or a function of the error and the performance criteria listed in Table I. b. are readily applicable for optimal control. One performance criterion[14] recently introduced is a two objective criterion in which the following integral is to be minimized.

$$\int_{0}^{\infty}\left[f_1(e) + f_2(m)\right]dt.$$

where

$f_1(e)$ is some function of error.

$f_2(m)$ is some function of manipulated variable.

DETERMINATION OF CONTROLLER TRANSFER FUNCTION.

a) Simple Time Invariant Systems:

These are the systems whose describing equations are completely known. They are simulated on an analog computer, usually with a three term controller. The controller parameters are chosen with respect to the selected performance criterion. The optimum value of the performance criterion results in best parameters of the controller and hence an optimum system. One such scheme is shown in Fig. 1.7. If "integral square error" criterion is chosen, the system equations can also be solved by usual mathematical techniques and optimum parameters of the controller obtained.

b) Complicated Time Variant Systems:

When little is known about a time varying system, and also, the performance criterion is a function of several variables with certain constraints, the use of the ordinary techniques for the adjustment of optimum controller parameters becomes impractical. The existence of constraints is one such feature which in some cases cannot be handled by the calculus of variations. Moreover, often used trial and error methods for optimization are likely to be inefficient and practically impossible to program on a digital computer. In a situation like this "gradient techniques" are the compromise between the above two. Usually the performance criterion may be expected to have an extremum

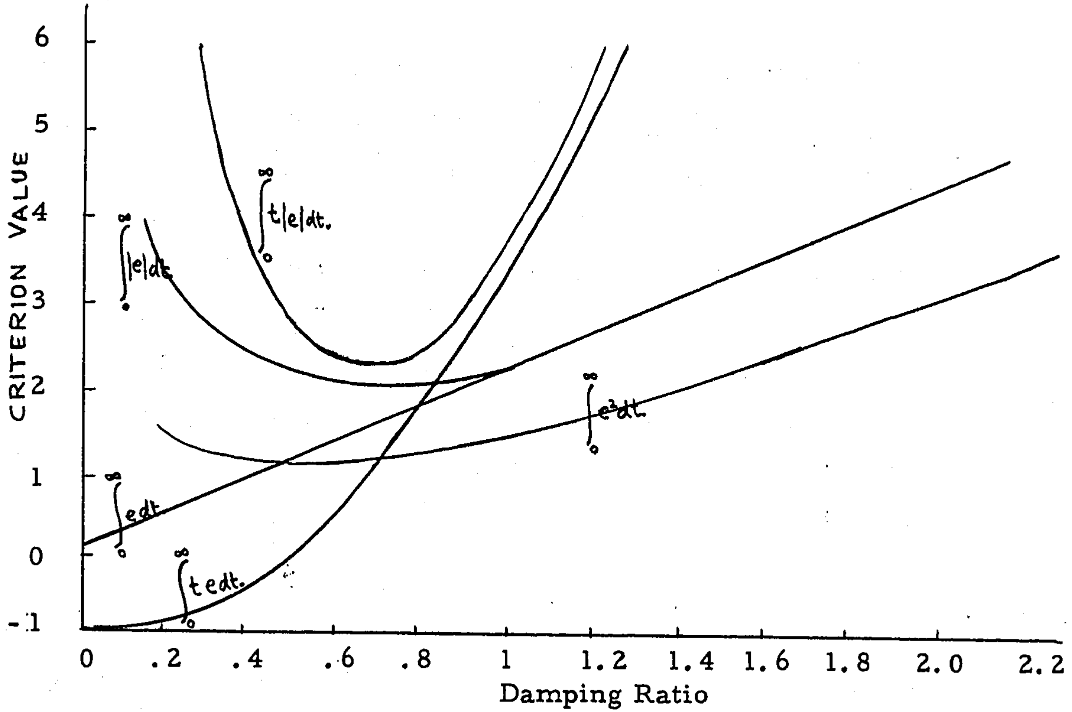


Fig. 1.6. Selectivity of Criteria for the Step Function on Second Order System.

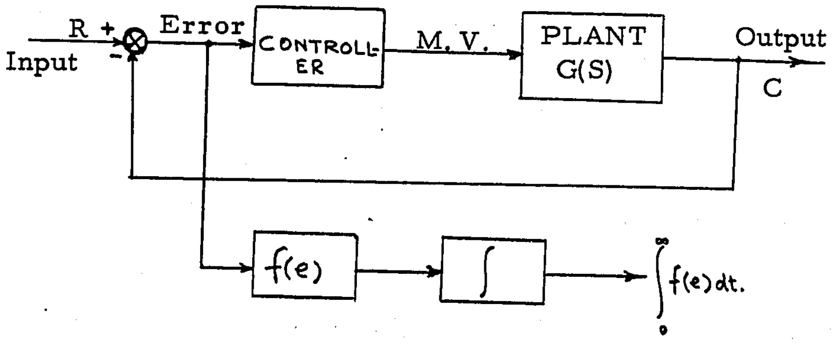


Fig. 1.7. A Simple Scheme for Obtaining an Optimum System.

i. e. it is an "even" function, and thus general search problem is one of hill climbing (or Valley-descending). Hill-climbing is the method which finds local gradient of either single or multivariable systems and climbs the hill using this gradient information, which is the basis of steep ascent technique. One such scheme is shown in Fig. 1.8. This steep ascent method of minimizing a certain function consists essentially of steps (ii-v) mentioned in conjunction with the definition of optimal control. For the sake of continuity, they are mentioned again with the addition of initial steps:

i) Choice of a starting point.
ii) Making a "probe" step in one manipulated variable.
iii) Identification of the current value of the system performance criterion.
iv) Comparison with the recent list value of the performance criterion.
v) Decision to move to a state, where a better value of the performance criterion may be obtained.
vi) Repetition of the cycle.

Fig. 1.9 shows the typical optimizing trajectories.

With multivariable performance criterion successive probing steps may be made in each variable to obtain a maximum combined gradient. Feldbaum[15, 16] has used this basic technique in his 12-variable optimalizer. The measure of error has been chosen as the mathematical expectation of the output. In his paper, Feldbaum has also discussed the magnitude of the probing steps in relation to the magnitude of interference. Milsum[14] has introduced a simpler technique of testing each variable in turn and making appropriate step after each test. This technique is not as efficient as that of Feldbaum, but it is easy to instrument on an analog computer.

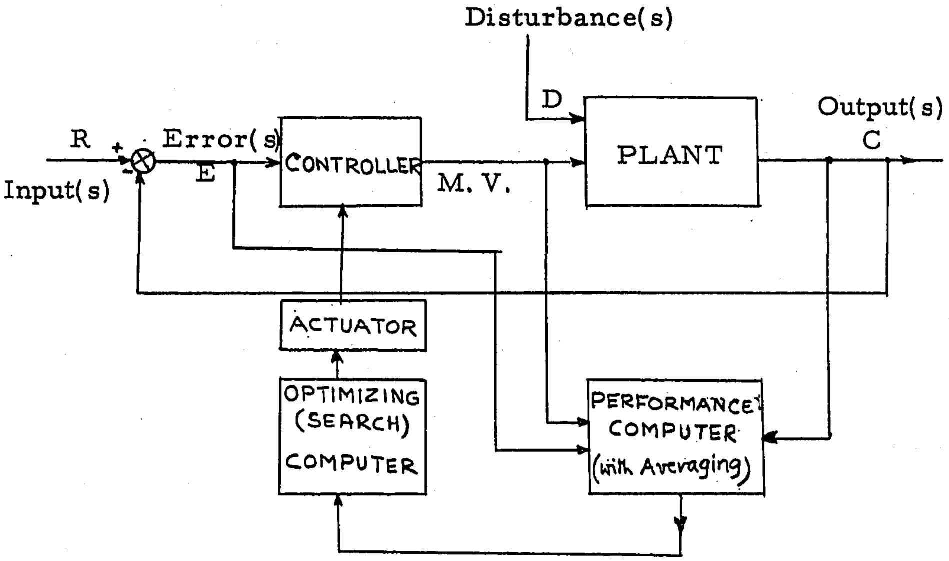


Fig. 1.8. Optimal Control Configuration

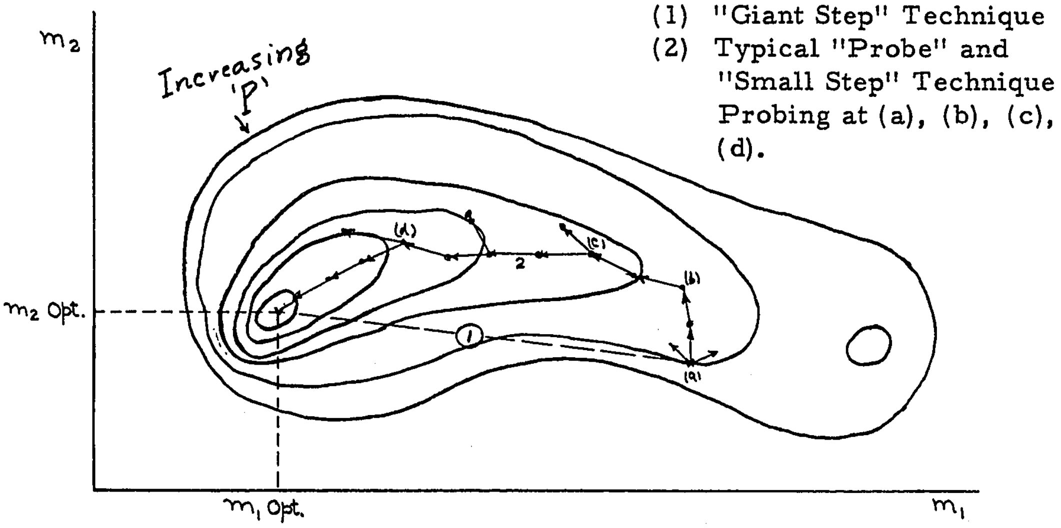


Fig. 1.9. Typical Optimizing Trajectories.

In the conclusions, it may be remarked, that the function of manipulated variables may have several extremum values. In such a case, one may not know, whether the right peak is attained. The only way to ensure convergence upon the global optimum, when the gradient of the performance criterion ceases to improve further, is to give a giant step by determinate or random technique. Then the gradient of the performance criterion should be tested. If the gradient improves, further steps should be continued to seek the right peak. If the gradient shows worsening, the peak obtained previously was the right one.

CHAPTER II

i) Some Considerations on the Application of Existing Control Theory to Chemical Processes.

The ambition of the process engineer is to design fully automatic continually optimized plants. So far, there may be quite a few plants, which really fulfill this ambition. When this requirement in the plant design was recognized, people tried to devise suitable controls. Nevertheless, apart from few exceptions, the control of chemical processes has not been very satisfactory. The main factor adversely affecting a satisfactory control is the lack of sufficient knowledge[17] of chemical processes. Distinctive features of the chemical and mechanical systems are summarized in Table II[18], wherefrom it can be appreciated why the control of chemical plants is not as satisfactory as that of mechanical plants.

Apart from the distinct features in Table II, chemical systems are multivariable processes, a large system may contain as many as 1000 variables. Out of these only a few are controlled directly. Others are assumed to have negligible effect. In mechanical systems of equal complexity, it is rare to have such a large system without some auxiliary objectives. This auxiliary objective allows the system to be broken in subsystems and permits each of these to be designed as an independent unit.

The slow response, propagation and hydrodynamic delays, little known reactions and inadequate measuring devices are the major factors which make control less effective in the process field.

ii) Binary Distillation Columns.

In fractionation, binary distillation as shown in Fig. 2.1 is the simplest process in which two streams of liquid (top and bottom

TABLE II

	Mechanical Systems		Chemical Systems
1)	The variations in the input are normally random, of short duration and uncontrolled.	1)	Random input variations are infrequent and sustain for a long period.
2)	System is fast i. e. response time and damping is small.	2)	Response time and damping are usually large.
3)	Frequent occurrence of disturbances and fast dynamic response of the system call for the necessity of optimization of the system.	3)	Changes are so infrequent that duration of transients is very short as compared to steady state, hence optimization is of little importance.
4)	Inputs are not normally measured.	4)	Inputs are generally measured.
5)	The only source available for detecting changes, is the system itself.	5)	Analytic devices are generally used with continuous processes.
6)	System performance is not sufficiently reproducible when based on varying input magnitudes (owing to the effects of nonlinearities).	6)	Performance is reproducible within acceptable limits. Some small benefits may be obtained by small adjustments dictated by the application of feedback concepts.
7)	Output is measurable.	7)	Output may be complex and difficult to measure correctly.

products) are produced. In this process, the separation depends upon the ratio of vapor to liquid, relative volatility of the components and effectiveness of mass transfer. The main components of the plant are:

1) Preheaters.
2) Tanks, pumps and flow measuring devices.
3) Reboiler.
4) Reflux condenser and accumulator.
5) Distillation column.

Feed stream at some predeterminee temperature enters the column through the feed plate and spreads in the column. Due to the downcoming stream of reflux, the concentration of the light key component increases in the ascending vapour, which increases the proportion of the light key component in the section above the feed plate. Hence, this section is termed as "enriching" or "rectifying" section. The vapor which ascends towards the top from the bottom of the column, is partially condensed due to the temperature gradient in the column. This condensation occurs particularly below the feed plate. Hence, the lower portion of the column is called "stripping" (exhausting) section. A typical temperature and composition distribution in a column is shown in Fig. 2.2. The factors which control the fractionation process are treated in some detail in the following section.

iii) Factors Controlling Distillation Process:

Temperature:

In consideration of the major role of the temperature in the process of distillation, a brief account of the importance of proper temperature at specific points is given here.

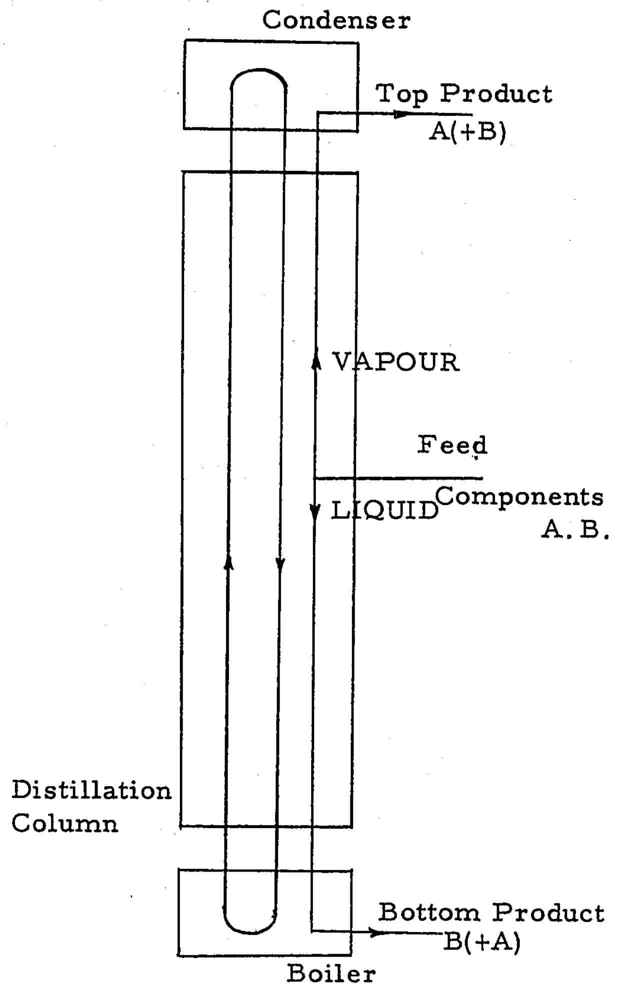


Fig. 2.1. Flow Conditions in a Binary Distillation Column.

Feed Temperature:

If the temperature of the feed is higher than the boiling temperature of the mixture, major portion of the feed is vaporized and the vapor will rise quickly in the "enriching" section. Consequently this section will be overloaded. Also, this will contaminate the overhead product with heavy component. Conversely, if the temperature is low, the "stripping" section will be overloaded and to avoid flooding, more heating will be required. To avoid the above situation, general practice is to keep the temperature of the feed equal to the temperature of the feed plate, obtained from the temperature gradient in the column. This also helps in eliminating the disturbance due to temperature difference of the liquid already on the feed plate and the entering liquid.

Top Plate Temperature:

The temperature at the top plate is the indication of the effectiveness of the separation. The separation is kept constant by maintaining a constant temperature. The temperature at the top should be high enough to just vaporize the top product. If the temperature is too high, the proportion of the bottom product will increase and the quality of the top product will be deteriorated. If the temperature is too low, some vapor will be condensed before going out of the top, which would decrease the output efficiency of the column.

Bottom Temperature:

The temperature at the bottom should be just sufficient to vaporize the given mixture. Higher temperature increases the speed of the vapor, which decreases the vapor-liquid contact time. Since the temperature drop of the vapor depends upon the vapor-liquid contact time, heavy key componant is not condensed appreciably. In order to bring the top product to the desired level,

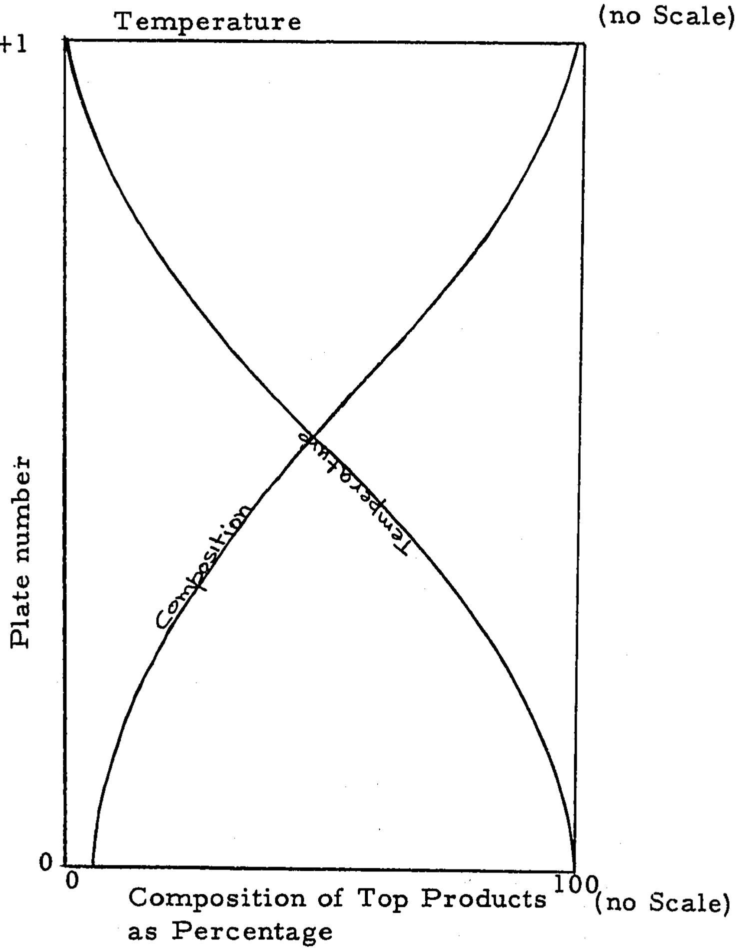


Fig. 2. 2. Temperature and Composition Distribution in a Binary Distillation Column.

the quantity of the reflux should be increased. The argument given above shows that higher temperature of the reboiler increases both the cost of heating and operation. If the temperature of the reboiler is too low, the speed of the vapor is very small. In this case, although the top product is rich, yet desired output efficiency is not attained.

The importance of the proper temperature is apparent from the fact that in adjusting conditions for better operations, a majority of the relevant factors involves temperature.

1) Temperature of the feed.
2) Temperature of the reflux.
3) Reflux flow.
4) Column pressure.
5) Temperature of reboiler.

Pressure:

In fractionation, since temperature required to boil a mixture is directly proportional to the pressure, low pressure requires low temperature for separation so that the cost of operation is appreciably reduced. Columns, which are used for a mixture that has light key component, usually work on their own vapor pressure. Similar to temperature, pressure also has a gradient, but this gradient is not very prominent in columns which operate on their own vapor pressure. The vapor pressure in such columns mainly depends upon the temperature and quantity of the cooling medium. If the reflux accummulator is open to atmosphere, the column will be virtually operating at atmospheric pressure.

Reflux:

In preceding sections, the importance of the reflux has been occasionally mentioned. Reflux effects the process of distillation in two ways. First, relatively cold downcoming liquid (reflux) extracts the latent heat of the heavier component, which condenses and joins descending liquid. Second, the rising vapor helps in the vaporization of the lighter component from the reflux stream which joins ascending vapor. In brief, reflux helps fractionation in the following ways:

1) Makes fractionation possible and improves fractionation.
2) Serves to reduce the amount of heavy component in the upcoming vapor, and
3) Removes excessive heat from the distillation column and thus controls its temperature distribution.

To minimize the disturbance, the reflux is commonly introduced at the top plate.

Contactors:

The main function of the contactors is to provide non-effective contact between ascending vapor and descending liquid. The efficiency of the contacting process depends upon: 1) type of contactors, 2) dynamics of the fluids, 3) properties of the fluid. The effectiveness of a contactor is determined by its ability to exchange the components between vapor and liquid. Among various contactors, which are in use, grid trays, bubble cap trays and float valve bubble trays are most popular.

Feed Plate Location:

The choice of the feed plate is not governed strictly by any rule. The choice of the location of the feed plate approximately depends upon the desired quality of the top product and the original composition of the feed. Improper selection of the feed plate makes distillation more difficult in one of the sections. If the feed plate location is too high in the column, the "enriching" section of the column will be too short to achieve effective rectification. Similarly, if the feed plate location is too low, stripping will not be very effective.

Before concluding this section consideration of the structure and design of a column, in general, seems to be appropriate. The plates should be level, supported by support rings and must be properly spaced. The space between trays determines the capacity of the column. It is this spacing that creates the gravity head of the liquid. It depens on (1) velocity of ascending vapor, (2) characteristic of the vapor and, (3) the depth of the liquid on the plate. The number of plates, the spacing between them, the liquid accummulator depth at the bottom of the column, and the height of the liquid disengaging space above the top tray determine the height of the column.

iv) Control of Distillation Columns.

The automatic control of distillation columns, due to its importance in industry, has been given considerable attention by many research workers. Efforts have been made to find a solution using almost every available method. This automatic control has been considered from two main points of view. First, authors have reported the experience of many years in practical applications of control[19, 20]. The rules provided by these authors are in general quite satisfactory. Nevertheless, these rules cannot be taken as the absolute basis for automatic control, because there remains such situation where control is known to be difficult and these rules become inapplicable. There is disagreement about the relative merits of different approaches of achieving control. This aspect will not be considered in this thesis. Second, attempts have been made to establish a theoretical basis for the design of the control systems. A great deal of this work is analytic[21-24], the remainder is based on the use of analog and digital computers[24-41]. Experimental and theoretical work has been compared[33, 34, 39-41] to establish the validity of the approach. It may be concluded that prediction of the dynamic response of the column is laborious and time consuming. This difficulty is due to the fact that control of the column depends mainly on the secondary effects (hydrodynamic delays, level control, time delays in condenser and reboiler, vapor hold up, etc.) about which little is known. Though, the equations of the mass transfer in a distillation column are easy to formulate, in their general form, they cannot be solved analytically. Also, the theoretical treatment of this problem is limited by the drastic assumptions such as the following:

1) column is at equilibrium when the change in the reflux rate is made at $t = 0$.
2) the plate efficiency is the same for all plates and reboiler and is independent of reboil or reflux (the plate efficiency varies directly as reflux and inversely as reboil).
3) the plate efficiency under non equilibrium during a transient experiment has the same value as under steady state conditions.
4) the liquid hold-up on the plates is perfectly mixed and independent of liquid flow rate.
5) the column operates adiabatically.
6) the molar volumes and latent heat are independent of composition.

7) the pressure is constant throughout the column.

8) the vapor hold-up is negligible.

9) the time to attain fluid dynamic equilibrium is small compared with the time of mass transfer.

10) the feed enters the column as saturated liquid.

11) murphree vapor efficiency is independent of time.

Murphree efficiency is defined as:

$$Em = \frac{y_i - y_o}{y_i - y_e^*}$$

where:

Em is the Murphree vapor efficiency.

y_i, y_o are average composition of vapor entering and leaving a plate.

y_e^* is composition of vapor in equilibrium with liquid flowing to plate below.

The equations formed for the material balance for any plate 'k' can in general be written as:

$$\frac{d}{dt}(H_k x'_k + h_k y'_k) = V_{k-1} Y_{k-1} - V_k Y_{k-1} - V_k Y_k + L_{k+1} x_{k+1} - L_k x_k + F_k Z_k$$

where:

H = Liquid hold-up (mols).

h = Vapor hold-up (mols).

x' = Defined so that Hx' is the amount in mols. of the more volatile component in the hold-up H.

y' = Defined so that Hy is the amount in mols. of the more volatile component in the hold-up h.

V = Vapor flow-rate (mols per sec.).

L = Liquid flow-rate (mols per sec.).

F = Feee rate (mols per sec.).

Z = Mol. fraction of the more volatile component in the feed.

The equations for all the plates in the column, reboiler and condenser can be written similarly. After a suitable description of the column is obtained, the simplifying assumptions are made and the solution obtained by any of the following methods.

v) Various Approaches for Modelling the Binary Distillation Column.

a) Laplace Transform Method:

This method is restrictive in the sense that it requires[21] linearization of the vapor-liquid equilibrium curve i. e. $y = ax + b$. Approximations involved in this method do not permit its use in specific cases, therefore, it is used for general study of distillation column.

b) Graphical Method:

This method gives some insight into the physical behaviour of the column, but the labor involved and limited accuracy prohibit its use in practice.

c) Analog Computers:

Provided the column is small (which is not true in general), analog computer is ideal for reasonable solution of these equations.

Since analog computers usually have limited number of components, larger columns cannot be handled by this method.

d) Digital Computers:

When an average column is considered as a whole, the number of equations needed for its full description is usually more than a hundred. Such a set of equations is almost impossible to solve analytically or graphically. In a situation like this, solution can always be obtained on a digital computer. This method is neither very accurate nor economic, still it is quite popular due to the fact that it is capable of handling a full description of the column and in this way gives an insight into the physical behaviour of each plate in the column. The information obtained in this way is ideally suited for design purpose of a column. Nevertheless, the cost and time involved do not justify its use in the design of automatic control loop for a column.

e) Perturbation Method, its Justification and Application.

In the process design, the usual approach has been in terms of steady state characteristics for which a great deal of data is available. From the view point of automatic control of a system, the information regarding the behavior of the system under changing conditions is necessary, which determines the controllability of the system. In most of the cases, qualitative information regarding the dynamic response of the process is available, which is useful in the determination of the steady state response of the process. In the determination of controllability of the plant, dynamic responses of the measuring devices, the control valves, the controller and the process are necessary. From these individual responses, the dynamic response of the complete control loop is obtained and the limits of the stability of system specified. Since the dynamic characteristics of the control devices are quite well known, the established theory of servomechanism can satisfactorily be applied for the synthesis of optimal controller parameters, if quantitative information regarding the dynamic performance of the system is available. This information can be obtained either from the design data or by experiment.

Essentially, one seeks the relation between the disturbance and the controlled variable and the relation between control action and the controlled variable. The disturbance could be in the form of impulse, step, ramp or sine wave. Out of these, step and sine wave are most commonly used. Since it is essentially a linearization of a complex system around its operating point, the amplitude and frequency of the disturbance are to be chosen with great care. If the amplitude of the disturbance is too small, it may not be able to change the output of the system appreciably, which will make the change in the output difficult to detect. On the other hand, if the amplitude of disturbing signal is too large, the response of the system to this change may not be linear. In that case linear relations between control action and controlled variable cannot be maintained and perturbation technique becomes useless.
As mentioned earlier, in process control, all the variables which affect the process and which can be controlled are kept constant, except one or two. These variables are then regulated by the main controllers to maintain the most important variable of the process at the desired value under all kinds of disturbances.

In a distillation column, the process variables to be controlled may be any of the following[41]:

i) concentration on some specific plates of the column,
ii) temperature on some specific plates of the column,
iii) column pressure,
iv) rate of flow of products,
v) liquid level in reboiler or condenser.

If a column is operating under atmospheric pressure then column pressure is not important. The flow rates and liquid levels are not as sensitive to disturbances as composition or temperature. Since composition is inversely related to temperature, either of them has almost the same sensitivity. The corrective media (manipulated variables) could be:

i) reflux,
ii) reboil,
iii) supply of coolant to the system,
iv) feed rate, and
v) rate of removal of products.

(iii-v) are not as effective as reflux or reboil. When one manipulated variable is used, reflux is preferred due to its fast corrective action. When both reflux and reboil are used as manipulated variables, there arises the problem of interaction.

Assuming that heating and cooling media are maintained constant, the possible disturbances most likely to affect the system are:

i) feed composition,
ii) feed enthalpy,
iii) feed rate.

The feed enthalpy and feed rate can be maintained at constant value by electric preheater and a good valve. The disturbance due to the feed composition is most likely to occur in a large sample of feed.

From the above considerations, if the change in composition on some specific plates (the choice of the most suitable plates will be discussed later) of column be obtained for a change in feed composition, reflux and reboil; then an appropriate control loop can be built around the specific plates to maintain their respective composition at the desired value. A typical control loop for the column is shown in Fig. 2.3.

This method is quick, less expensive and provides the information regarding the dynamic characteristics of the column under the true operating conditions, which is the basis for the automatic control.

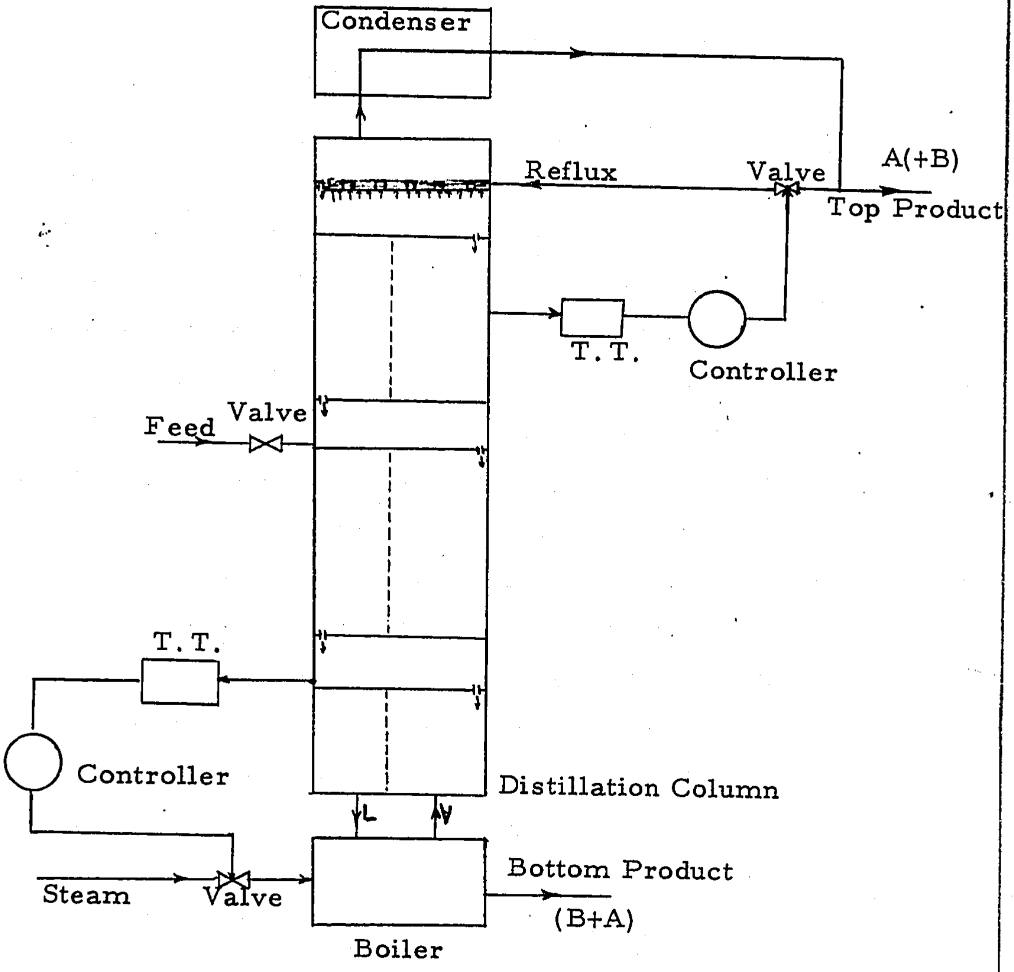


Fig. 2.3. A Typical Scheme for Automatic Control of a Binary Distillation Column.

CHAPTER III

1) General Description of the Column.

The column on which the experimentation for the realization of the automatic control was undertaken is shown in Fig. 3.1. In addition to reboiler and condenser, this column has ten plates. Each plate is 15·24 cm. in diameter, spaced 15·24 cm. apart and has 5 bubble caps and one downcomer. Each bubble cap is 3.5 cm. in diameter, 2.5 cm. in height and has 26 rectangular slots of ·15 cm^2 area for perfect mixing. The downcomer pipe has a diameter of 1.905 cm. The column has 2.54 cm. thick insulation of cellular asbestos to reduce the loss of heat. Facility for reading liquid temperature of each plate with thermocouples is provided by insertion of copper tubes in the bottom of each plate. Each plate is also provided with a monitor valve to permit an occasional check for the liquid level in the plate. The column could be fed at three distinct plates, namely, the bottom plate, the fifth, or the top plate. the steam supply to the boiler of the column is taken from the main supply line and is regulated through a valve and mercury manometer. Steam is also provided for preheating the feed and is controlled by a separate steam valve and pressure gauge. In order to heat the reflux to the desired temperature and have a quick and accurate control of the temperature, both steam and electric heating are used. The temperature at each point mentioned above can be read (though not very accurately) with the help of thermometers connected in each line. The water is used as the cooling medium and enters the condenser at approximately 15 degree Centigrades. There are two feed tanks, two product tanks, and one reflux accummulator. The feed tanks and the reflux accummulator are open to atmosphere, so as to make the column operate at the atmospheric pressure. The feed and reflux are pumped into the column with pumps of 1/2 and 1/8 h.p. respectively and the flow is measured and regulated with the help of valves and rotameters, connected between pumps

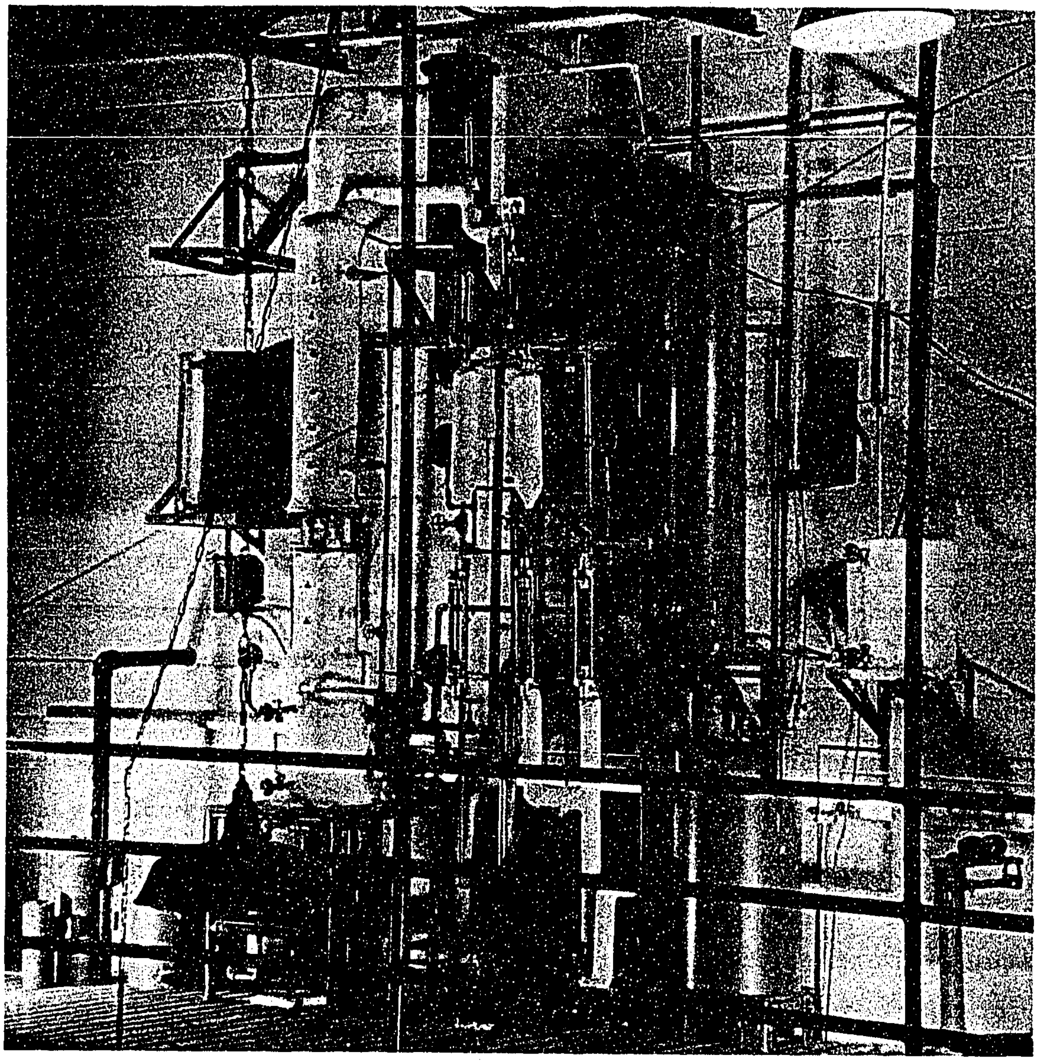


Fig. 3.1. The 10-plate Binary Distillation Column.

and preheaters. Feed pipes (1.905 cm. diameter) are connected in such a way that one tank could be switched off and the other switched on almost instantaneously without disturbing the system.

ii) The Measurement of Composition.

The composition of the mixture at a particular plate could be measured by any of the following methods:

a) Hydrometer method,
b) refractive index method,
c) temperature measurement method.

The measurement of the composition by hydrometer method is unsatisfactory because of the fact that it is an indirect method and has limited accuracy. Moreover, this method does not permit quick measurement of the composition, because the sample should be cooled down to 20 degree centigrade before any measurement. (The information regarding the composition relationship above 20 degree C is not available in literature). The refractive index method is fairly satisfactory from the point of view of accuracy. However, the methanol and water have comparable refractive indices. It makes this method inapplicable in the present case. Thus one is left with the indirect method of measuring the composition by its temperature measurement. For a certain pressure, there exists a temperature at which the liquid and the vapor of a particular mixture, when in complete equilibrium, represent a certain composition. The accuracy in the determination of the composition mainly depends upon the condition of the column and the temperature measuring device (thermocouples and potentiometer). Since low temperatures were involved, iron-constantan thermocouples were used for this measurement. The potentiometer, Fig. 3.2 used, had three input terminals and could read down to 10^{-7} volts. The emf indicated by the potentiometer represents a certain temperature, which in turn is related to the composition.

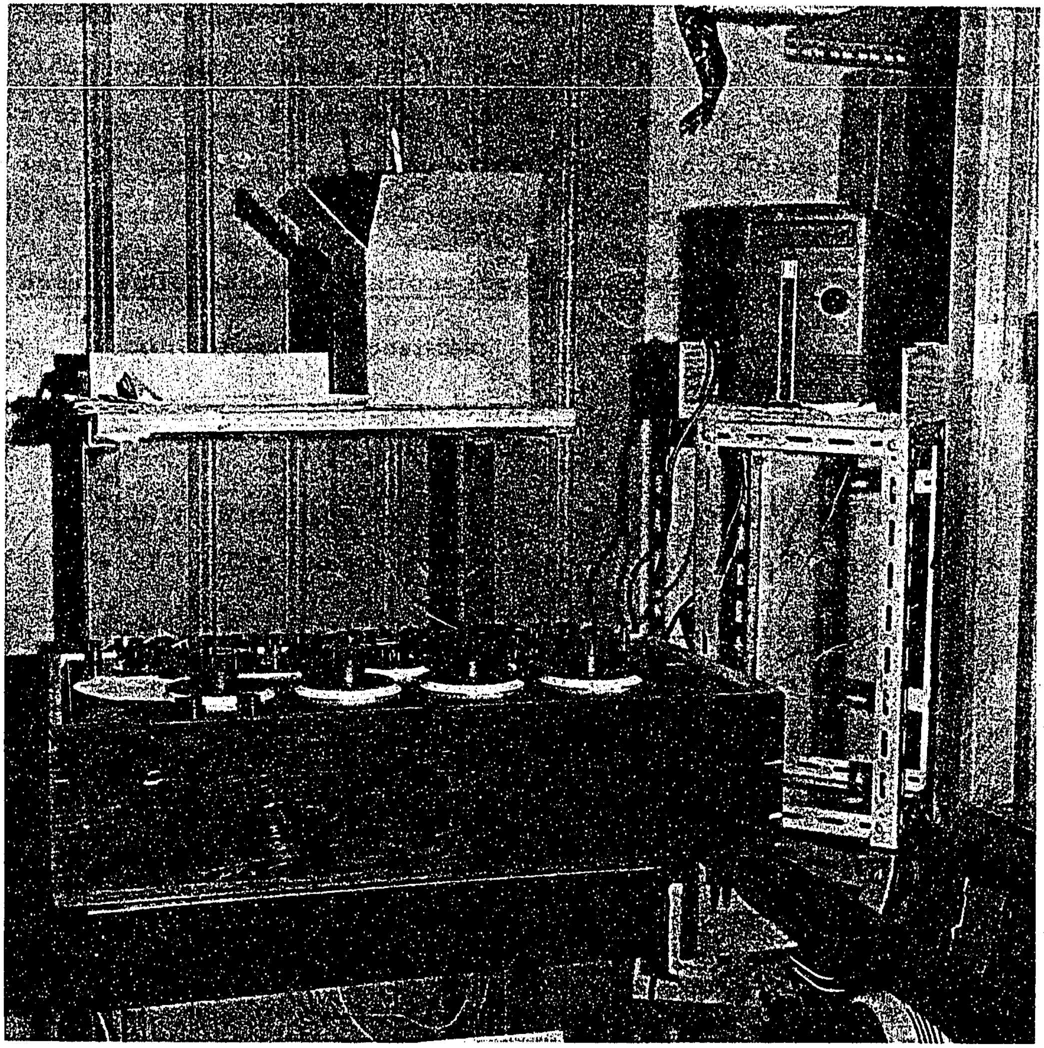


Fig. 3.2. 3-Terminal Potentiometer

iii) Calibration of Rotameters.

Since there was no information available regarding the calibration of rotameters, they were calibrated using water as the standard for each rotameter reading, time taken to fill a 100 c.c. jar was recorded and average of three readings was taken. Later, the flow was corrected for desired composition for respective rotameters. Corrected calibration tables and curves for fee , reflux and product are given in Appendix I.

iv) Specification of the Conditions for the Operation of the Column.

a)	Feed Composition:	
	Methanol-Water (CH_3OH -H_2O)	50:50 (by weight)
b)	Feed flow rate	400 gms/min.
c)	Top product separation	93.00%

Steam pressure of 9 p.s.i. for the boiler and a flow of 60 lbs/min. of water at about 15°C for the condenser was found to be most suitable for the above specifications.

v) Determination of the Reflux Ratio for the Specified Separation.

In order to determine the optimum reflux ratio, feed composition, feed flow, rate of the boil up and rate of cooling medium were kept constant and the quantity of the reflux entering the column through the top plate was varied. For each value of the reflux, the composition of the top product was determined by temperature measurement. The readings are tabulated in Table III. a. and Fig. 3.3 shows the curve of the variation of the composition of the top product as a function of reflux. It was found that a reflux ratio of 50:50 is required for 93.00 percent separation.

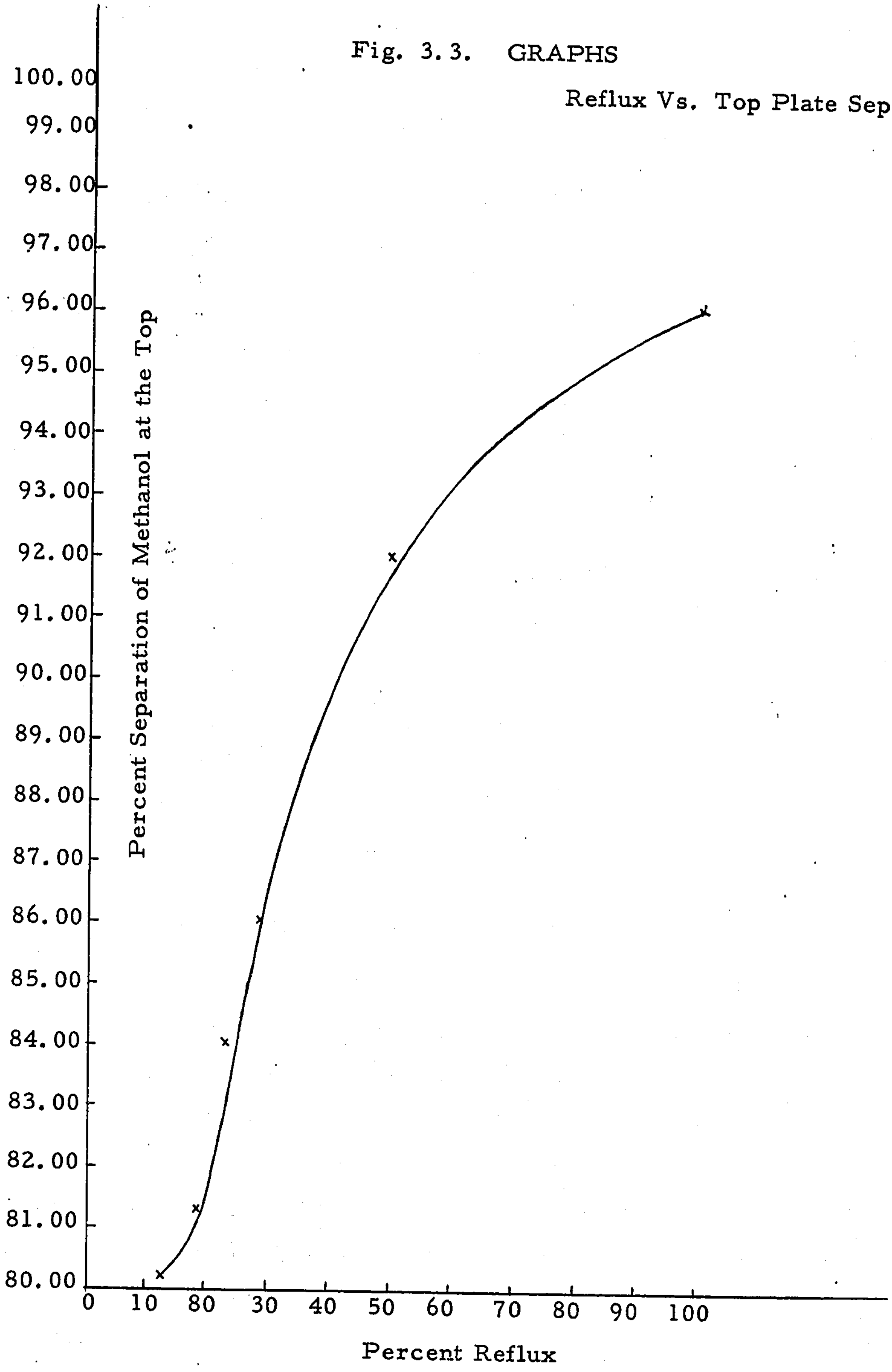
TABLE III. a

No:	Percentage Reflux	% Top plate Separation (Methanol)
1	12.5	80.2
2	18.18	81.3
3	22.40	84.0
4	28.00	86.00
5	49.00	92.00
6	100.00	96.00

vi) Distribution of the Composition in the Column.

When the column was operating under specified conditions, the composition distribution of the column was determined. It was found that the behaviour of the column is quite normal in the sense that in the bottom and top sections, there is slow change in the composition due to the presence of high proportion of heavy and light key components in respective sections and in the middle of the column, the composition gradient is comparatively steep. It also shows that top and bottom sections are not very sensitive to disturbances in the column. Readings are tabulated in Table III. b, Fig. 3.4 shows composition distribution in the column.

Fig. 3.3. GRAPHS



Reflux Vs. Top Plate Separation

Table III. b

Composition Distribution in the Column

Plate	Voltage (mv)	Temperature ^oF	Composition of CH_3OH (Liquid)
1	4.464	188.00	12.00
2	4.390	182.00	17.00
3	-	-	-
4	4.047	170.00	32.50
5	3.930	167.60	38.00
6	3.857	165.00	44.00
7	3.780	162.40	50.00
8	3.600	156.00	70.00
9	3.520	154.00	82.00
10	3.480	152.00	90.00

vii) Theoretical Plate Efficiency of the Column.

Theoretical plate efficiency is defined as the ratio of the number of plates, required theoretically for a certain top plate composition, to the actual number of plates in the column. It is a function of vapor-liquid contact, feed composition, location of feed plate, reflux ratio and reboil. The number of theoretical plates is determined from the vapor liquid equilibrium diagram. Fig. 3.5 shows the construction for the determination of theoretical plates. The theoretical plate efficiency of the column from the diagram comes out to be 80%, which is quite reasonable.

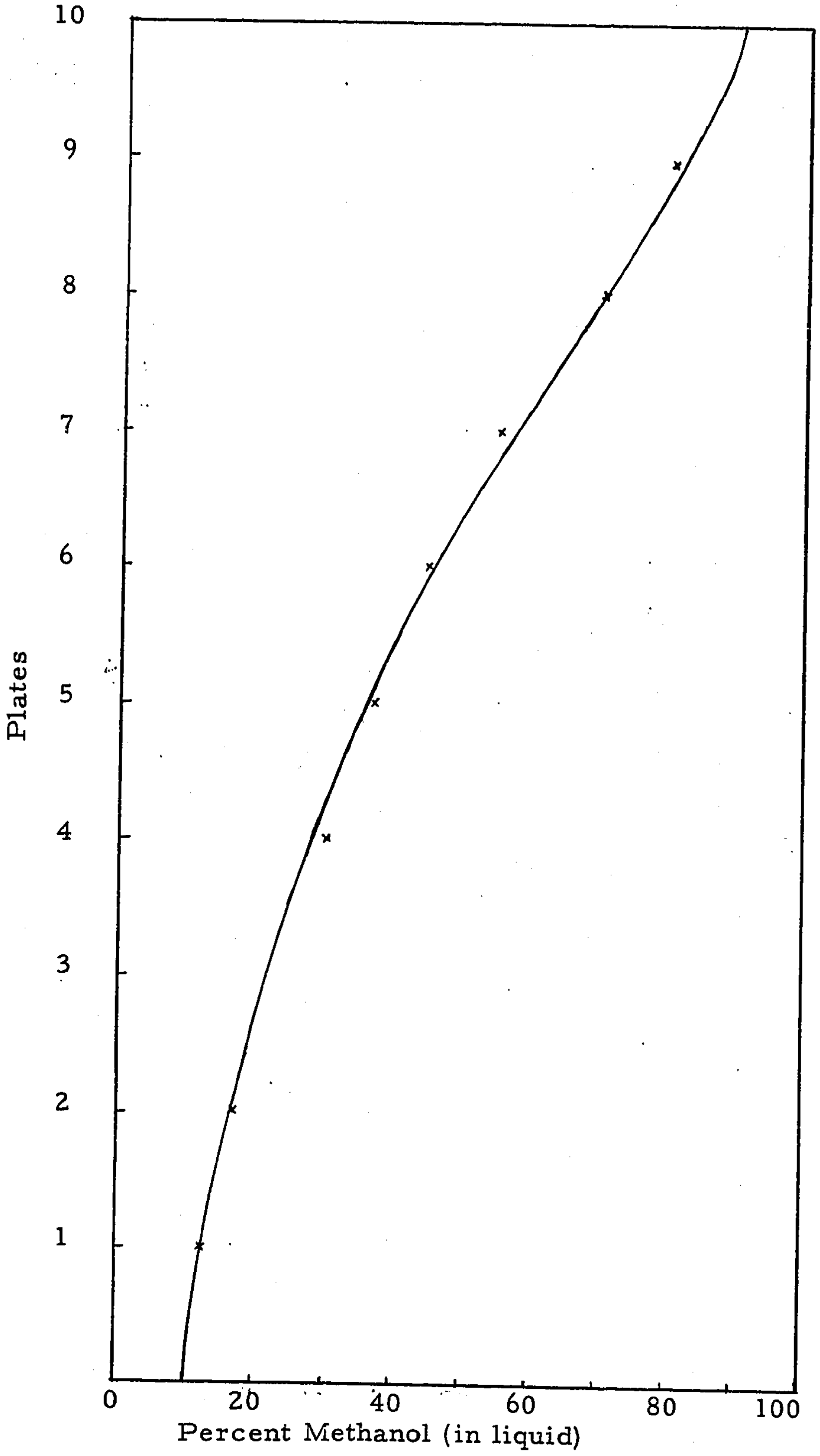


Fig. 3.4. Composition Distribution in the Column.

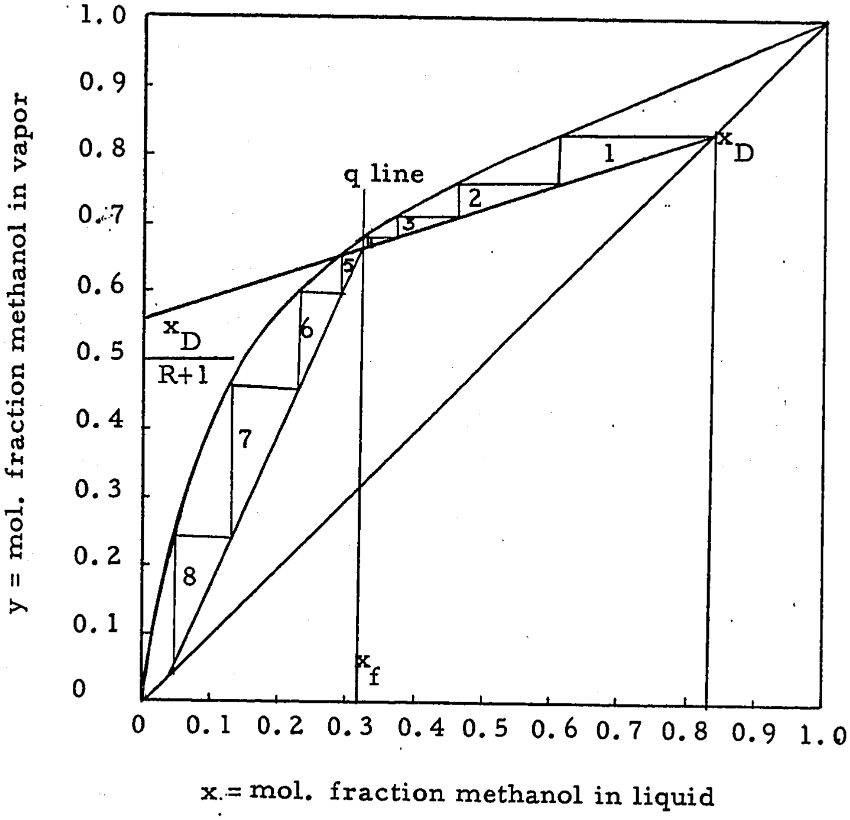


Fig. 3.5. Determination of the Number of Theoretical Plates.

viii) Determination of the Plates for the Most Effective Control.

In the control of the distillation columns, the choice of the representative plates determines the effectiveness and reliability of the control. The suitability of the plates is determined by the following factors: 1) time taken in the propagation of the disturbance to the reference plate, 2) sensitivity of the plate, and 3) the deterioration of the output composition in the presence of disturbances.

In the control of the distillation columns either top or bottom or some intermediate plate is used for sampling the output. Since intermediate plates are nearer to the feed plate, they have relatively small dead zone, which determines the linearity of the system.

In the intermediate plates the proportions of the components are low as compared to the top or bottom plate, which makes the plates more sensitive. Moreover, the choice of the intermediate plate has definite advantage over the top or the bottom plate in the sense that the disturbance is dissipated within the column and the output composition remains constant in presence of disturbances.

Representative plates for one (reflux) and two (reflux and reboil) manipulated variables control are determined by the following expressions(42):

$$x_a = \tfrac{1}{2}(x_o + x_{n+1})$$

$$x_{b_1} = x_f + \frac{1}{4}(x_{n+1} - x_o)$$

$$x_{b_2} = x_f - \frac{1}{4}(x_{n+1} - x_o).$$

where:

x_a = liquid composition of the light key component at the required plate.

x_o = liquid composition of the light key component at the bottom.

x_{n+1} = liquid composition of the light key component at the top.

x_f = liquid composition of the light key component at the feed plate.

x_{b_1}, x_{b_2} = liquid composition of the light key component at the required plates.

The plate with "x_a" is most suitable for one manipulated control. Similarly, the plates with x_{b_1} and x_{b_2} are most suitable for two manipulated control. The values of x_f, x_o and x_{n+1} are obtained from Fig. 3.4, and substituted in the above expressions to obtain x_a, x_{b_1} and x_{b_2}. It is found that plate "7" and plates "7" and "2" are most suitable for one manipulated and two manipulated control respectively.

CHAPTER IV

i) Technique of Imposing Composition Test.

In order to simplify the diagram, those components of the plant which remain unchanged during the experiment, are not shown in Fig. 4.1. As mentioned in Chapter II, the technique involves linearization of the system around its operating point. During the test, reflux and reboil were kept constant and it was assumed that the superposition would be valid due to the linear characteristics of the system below a certain amplitude of the disturbance, after which the behaviour of the system would be quite uncertain. From the practical point of view, the composition in a large sample is quite unlikely to deviate beyond six percent from the average determined composition. In view of the above, a step change of 5.5 percent was considered to be quite reasonable. To ascertain that the behaviour of the column was actually linear, both positive and negative disturbances were given in the feed composition. It was found that the amplitude and the shape of the change in the output of plates "7" and "2" was nearly the same in either case, which confirmed linearity in the system. Another important consideration was to maintain the enthalpy of the feed constant before and after the test. Transmission delay through pipe was determined from the flow and x-sectional area of the feed pipe, and was found to be 2.6 minutes. The transport delay from plate to plate was approximated to be 10 sec.

The column was operated under specified conditions. The feed to the column was given through tank "B". When the system was in equilibrium, valve "C" was closed and valve "D" opened simultaneously. The stop watch was started at the same instant of time. In this way the feed was given from tank "A", which had methanol-water composition of 47.25:52.75. The steam through the preheater was adjusted to keep the enthalpy of the feed constant. After the calculated time of

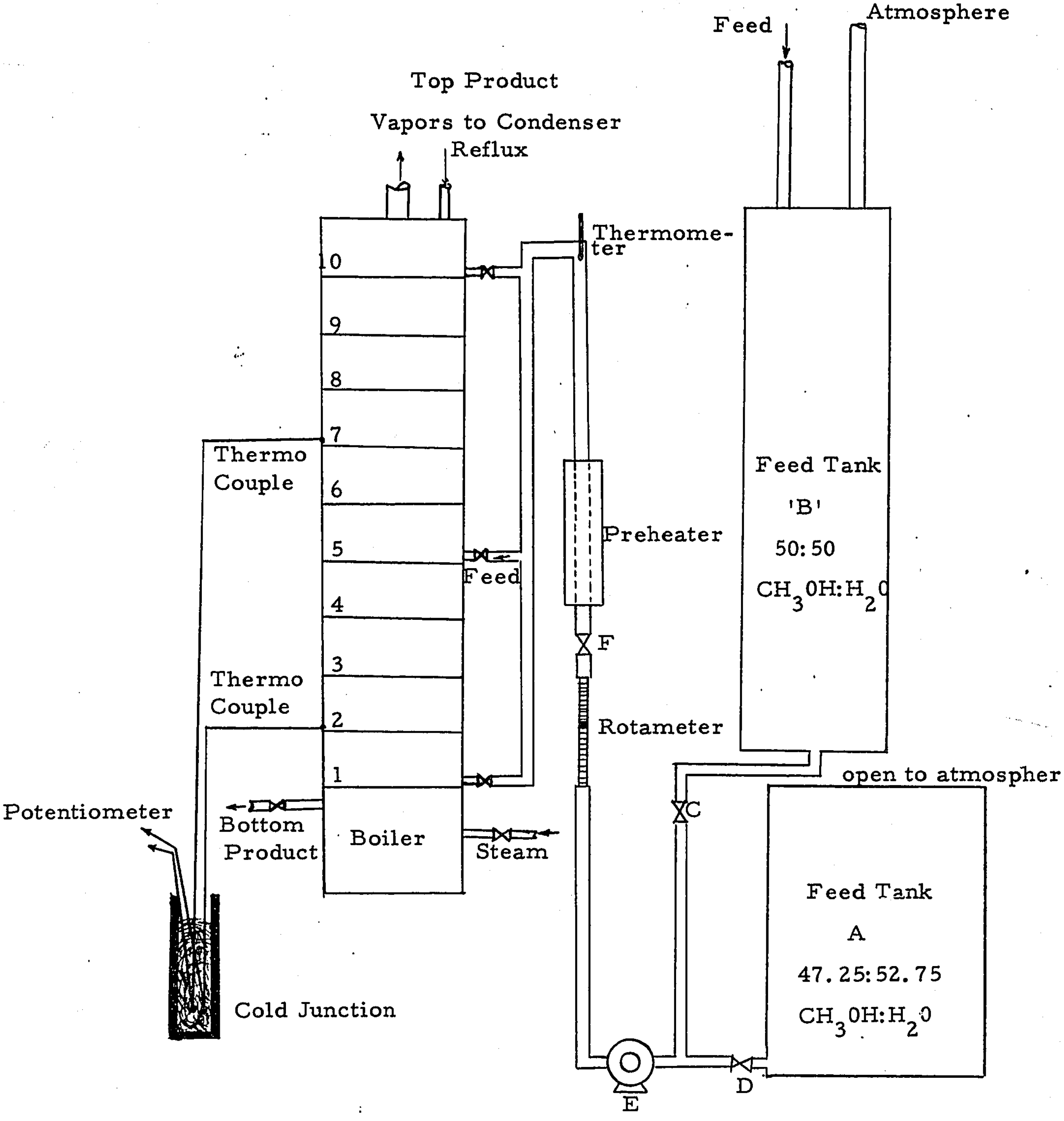


Fig. 4.1. Scheme for Imposing Composition Test.

transmission delay, the change in temperature of plates "7" and "2" was noted on the potentiometer. Similarly, for positive change, tank "A" was switched off and tank "B" switched on and changes in the output temperatures of plates "7" and "2" recorded. The data is given in Table IV a, b, c, d and Fig. 4-2. a. b. shows the resultant curves. It can be shown from the equilibrium diagram that the plate efficiency is directly affected by the change in feed composition.

Table IV-a

Composition Test

7th Plate

+ 5.5% Change

Transmission delay in pipe = 2.6 min.

Transport delay in plate = .3 min.

Time (min.)	Potentiometer Reading	Temperature °F	Absolute Change in Temperature	Composition % methanol	Absolute Change in Composition
0	3.8390	164.3800	0.0000	78.1200	0.0000
2	3.8381	164.3430	0.0370	78.1620	0.0420
5	3.8357	164.2700	0.1100	78.2700	0.1500
7	3.8277	164.0440	0.3360	78.4720	0.3520
10	3.8258	163.9660	0.4140	78.6650	0.5450
12	3.8249	163.9450	0.4350	78.6900	0.5700
15	3.8125	163.8550	0.5250	78.8200	0.7000
18	3.8202	163.8150	0.5650	78.8690	0.7490
20	3.8200	163.8140	0.5660	78.8700	0.7500
25	3.8200	163.8140	0.5660	78.8700	0.7500
30	3.8200	163.8140	0.5660	78.8700	0.7500
40	3.8197	163.8090	0.5710	78.8720	0.7520
50	3.8197	163.8090	0.5710	78.8720	0.7520

Table IV-b

Composition Test

7th Plate -5.5% Change

Transmission delay in pipe = 2.6 min.

Transport delay in plate = .3 min.

Time (min.)	Potentiometer Reading	Temperature °F	Absolute Change in Temperature	Composition % methanol	Absolute Change in Composition
0	3.8415	164.4000	0.0000	78.1000	0.0000
2	3.8442	164.4800	0.800	78.0000	0.1000
5	3.8481	164.6000	0.2000	77.8250	0.2750
7	3.8512	164.6900	0.2900	77.7160	0.3840
10	3.8572	164.8650	0.4650	77.4800	0.6200
12	3.8589	164.9250	0.5250	77.4000	0.7000
15	3.8599	164.9550	0.5550	77.3600	0.7400
18	3.8619	165.0050	0.6050	77.2900	0.8100
20	3.8619	165.0050	0.6050	77.2900	0.8100
25	3.8622	165.0070	0.6070	77.2880	0.8120
30	3.8630	165.0110	0.6110	77.2840	0.8160
40	3.8642	165.0250	0.6250	77.2830	0.8250
50	3.8642	165.0250	0.6250	77.2830	0.8250

Table IV-c

Composition Test

2nd Plate + 5% Change

Transmission delay in pipe = 2.6 min.

Transport delay in plate = .3 min.

Time (min.)	Potentiometer Reading	Temperature ^{o}F	Absolute Change in Temperature	Composition % methanol	Absolute Change in Composition
0	4.3705	182.0370	0.0000	52.9500	0.0000
2	4.3695	182.0050	0.3200	53.0120	0.0620
5	4.3650	181.8500	0.1870	53.2340	0.2840
7	4.3607	181.7220	0.3150	53.4120	0.4620
10	4.3560	181.5500	0.4870	53.6500	0.7000
12	4.3530	181.4600	0.5770	53.8120	0.8620
15	4.3510	181.3870	0.6500	53.9250	0.9750
18	4.3493	181.3320	0.7050	54.0120	1.0620
20	4.3481	181.3000	0.7370	54.0500	1.1000
25	4.3473	181.2670	0.7700	54.1120	1.1620
30	4.3468	181.2500	0.7870	54.1270	1.1770
40	4.3460	181.2180	0.8190	54.1870	1.2370
50	4.3455	181.2050	0.8320	54.2120	1.2620
60	4.3454	181.2000	0.8370	54.2170	1.2670

Table IV-d

Composition Test

2nd Plate

-5% Change

Transmission delay in pipe = 2.6 min.

Transport delay in plate = .3 min.

Time (min.)	Potentiometer Reading	Temperature °F	Absolute Change in Temperature	Composition % methanol	Absolute Change in Composition
0	4.3702	182.0260	0.0000	52.9700	0.0000
2	4.3712	182.0620	0.0360	52.9120	0.0570
5	4.3762	182.2300	0.2040	52.6620	0.3070
7	4.3800	182.3500	0.3240	52.4870	0.4830
10	4.3853	182.5260	0.5000	52.2120	0.7570
12	4.3880	182.6120	0.5860	52.0870	0.8820
15	4.3902	182.6950	0.6690	51.9620	1.0070
18	4.3917	182.7450	0.7190	51.8800	1.0900
20	4.3930	182.7870	0.7610	51.8250	1.1450
25	4.3937	182.8170	0.7910	51.7870	1.1820
30	4.3943	182.8260	0.8000	51.7620	1.2070
40	4.3952	182.8620	0.8360	51.7120	1.2570
50	4.3960	182.8780	0.8520	51.6820	1.2870
60	4.3962	182.8830	0.8570	51.6750	1.2950
70	4.3963	182.8830	0.8590	51.6760	1.2980

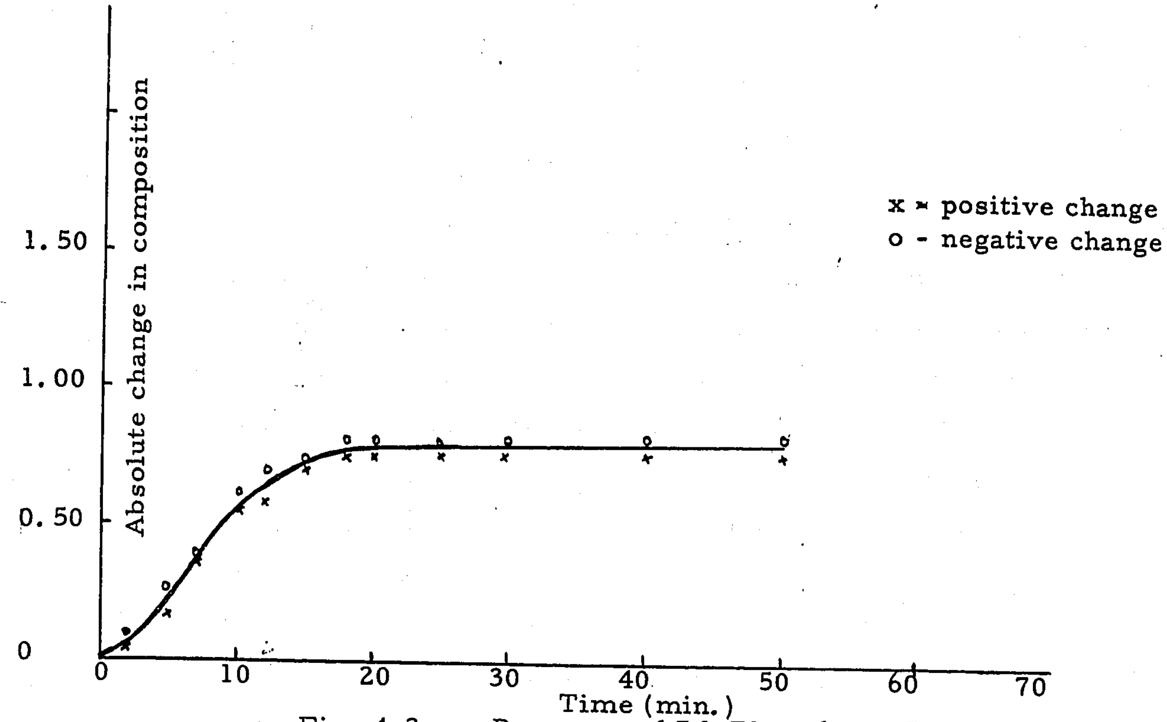


Fig. 4.2.a. Response of 7th Plate for a Step Change in Feed Composition.

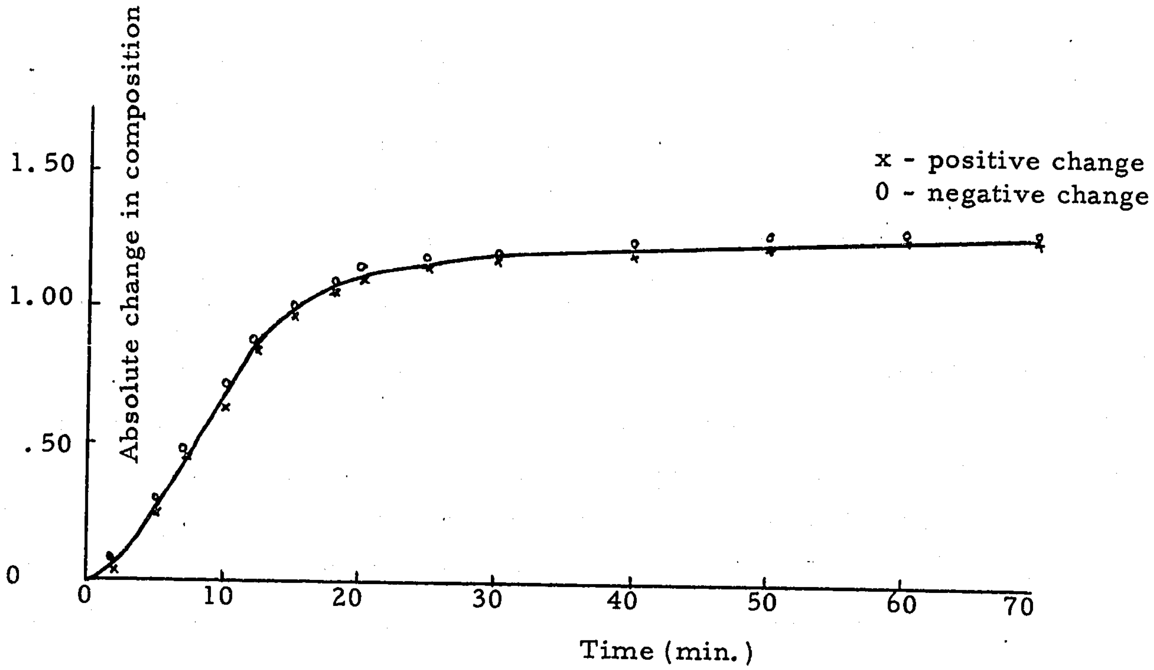


Fig. 4.2.b. Response of 2nd Plate for a Step Change in Feed Composition.

ii) Technique of Imposing Reflux Test.

The technique of imposing the reflux test was similar to the one employed in composition test. The linearity of the system was confirmed from the fact that changes in the temperatures of plate "7" and "2" were the same for positive and negative changes in the reflux ratio. The transmission delayin pipe was 3.4 minutes and plate to plate delay approximated to 10 sec. The condenser delay was neglected being comparatively smaller. The enthalpy of the reflux was maintained constant before and after the test with the help of preheater.

A step change of ± 10 percent in the reflux ratio was affected by operating valves "G" and "H" simultaneously as shown in Fig. 4.3. The stop watch was also started at the same time. After the predetermined time of propagation delay, changes in the temperature of plates "7" and "2" were noted with the help of the potentiometer.

The data obtained for plates "7" and "2" is tabulated in Tables IV e, f, g, h. Figs. 4.4 a, b, show the behaviour of the plates for an absolute change of 10 percent in the reflux ratio. It can be shown theoretically with the help of equilibrium diagram that plate efficiency increases with the increase of the reflux ratio and vice versa.

iii) Technique of Imposing Reboil Test.

The system was first operated under specified conditions. A change of ± 10 percent in the steam pressure was affected by changing the position of steam valve "K" as shown in Fig. 4.5. The linearity of the system was confirmed from the changes in the temperatures of plates "7" and "2" for positive and negative changes. The boiler delay, being very small, was neglected and the transport delay from plate to plate was approximated as 10 seconds.

The change in the temperature of plates "7" and "2" resulting from a change of ± 10 percent in the steam pressure was tabulated in

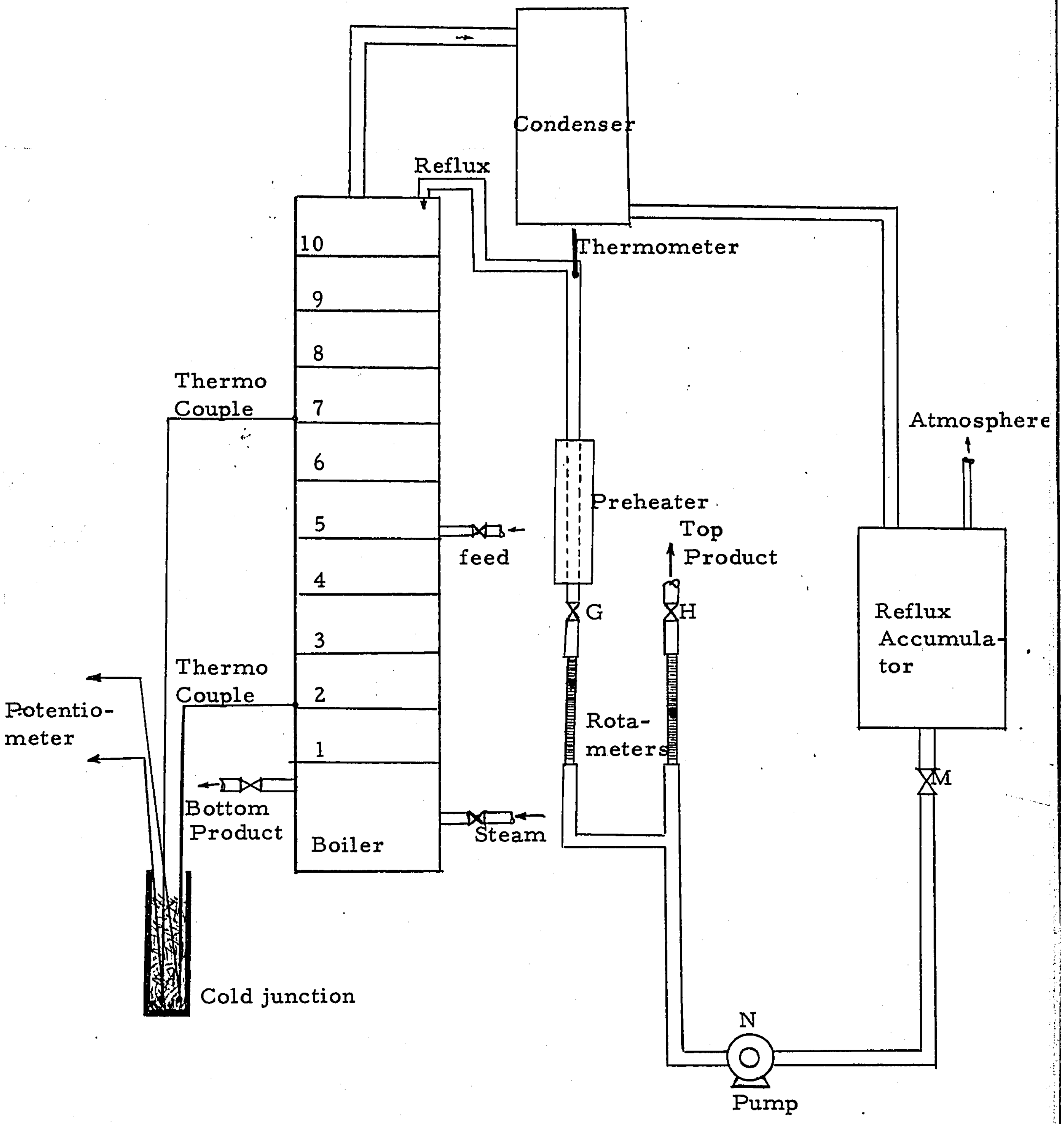


Fig. 4.3. Scheme for Imposing Reflux Test.

TABLE IV-e

Reflux Test

7th Plate +10% Change

Transmission delay in pipe = 3.4 min.

Transport delay in plate = .6 min.

Time (min.)	Potentiometer Reading (mv)	Temperature ^{o}F	Absolute Change in Temperature	Composition % methanol	Absolute Change in Composition
0	3.8426	164.500	0.000	78.000	0.000
2	3.8374	164.325	0.175	78.250	0.250
5	3.8276	163.960	0.540	78.730	0.730
7	3.8214	163.770	0.730	78.980	0.980
10	3.8170	163.580	0.920	79.200	1.200
12	3.8160	163.540	0.960	79.270	1.270
15	3.8132	163.450	1.050	79.398	1.398
18	3.8114	163.400	1.100	79.450	1.450
20	3.8110	163.375	1.125	79.500	1.500
25	3.8080	163.250	1.250	79.650	1.650
30	3.8078	163.249	1.251	79.652	1.652
40	3.8075	163.245	1.255	79.670	1.670
50	3.8026	163.075	1.425	79.900	1.900
60	3.8021	163.061	1.439	79.930	1.930
80	3.8020	163.060	1.440	79.932	1.932

TABLE IV-f

Reflux Test

7th Plate -10% Change

Transmission delay in pipe = 3.4 min.

Transport delay in plate = .6 min.

Time (min.)	Potentiometer Reading (mv)	Temperature ^{o}F	Absolute Change in Temperature	Composition % methanol	Absolute Change in Composition
0	3.8376	164.300	0.000	78.270	0.000
2	3.8418	164.470	0.170	78.050	0.220
5	3.8468	164.652	0.352	77.800	0.470
7	3.8525	164.832	0.532	77.550	0.720
10	3.8621	165.175	0.875	77.100	1.170
12	3.8658	165.300	1.000	76.930	1.340
15	3.8697	165.435	1.135	76.725	1.445
18	3.8725	165.570	1.270	76.570	1.700
20	3.8750	165.625	1.325	76.500	1.770
25	3.8772	165.700	1.400	76.400	1.870
30	3.8784	165.750	1.450	76.340	1.930
40	3.8790	165.760	1.460	76.330	1.940
50	3.8792	165.764	1.464	76.326	1.944
60	3.8793	165.766	1.466	76.324	1.946
80	3.8793	165.766	1.466	76.324	1.946

TABLE IV-g

Reflux Test

2nd Plate +10% Change

Transmission delay in pipe = 3.4 min.

Transport delay in plate = 1.2 min.

Time (min.)	Potentiometer Reading (mv)	Temperature ^oF	Absolute Change in Temperature	Composition % methanol	Absolute Change in Composition
0	4.3700	182.0170	0.0000	52.9880	0.0000
2	4.3698	182.0090	0.0070	52.9900	0.0020
5	4.3694	181.9920	0.0240	53.0200	0.0320
7	4.3689	181.9870	0.0290	53.0250	0.0370
10	4.3687	181.9800	0.0370	53.0370	0.0500
12	4.3686	181.9770	0.0400	53.0420	0.5500
15	4.3685	181.9730	0.0440	53.0500	0.0620
18	4.3684	181.9690	0.0480	53.0600	0.0700
20	4.3683	181.9650	0.0520	53.0620	0.0750
25	4.3682	181.9620	0.0450	53.0700	0.0820
30	4.3682	181.9520	0.0450	53.0700	0.0820
40	4.3681	181.9580	0.0490	53.0750	0.0870
50	4.3680	181.9550	0.0520	53.0800	0.0920
60	4.3679	181.9510	0.0560	53.0830	0.0950
70	4.3679	181.9510	0.0500	53.0830	0.0950

TABLE IV-h

Reflux Test

2nd Plate -10% Change

Transmission delay in pipe = 3.4 min.

Transport delay in plate = 1.2 min.

Time (min.)	Potentiometer Reading (mv)	Temperature ^oF	Absolute Change in Temperature	Composition % methanol	Absolute Change in Composition
0	4.3705	182.0370	0.0000	52.9500	0.0000
2	4.3706	182.0410	0.0035	52.9450	0.0050
5	4.3711	182.0570	0.0200	52.9250	0.0250
7	4.3715	182.0660	0.0290	52.9130	0.0370
10	4.3717	182.0730	0.0360	52.8920	0.0580
12	4.3718	182.0770	0.0400	52.8870	0.0620
15	4.3720	182.0850	0.0480	52.8750	0.0750
18	4.3722	182.09304	0.0550	52.8620	0.0870
20	4.3723	182.0970	0.0600	52.8550	0.0950
25	4.3723	182.0970	0.0600	52.8550	0.0950
30	4.3724	182.1010	0.0630	52.8500	0.1000
40	4.3725	182.1050	0.0670	52.8450	0.1050
50	4.3725	182.1050	0.0670	52.8450	0.1050
60	4.3726	182.1090	0.0710	52.8410	0.1090
70	4.3726	182.1090	0.0710	52.8410	0.1090

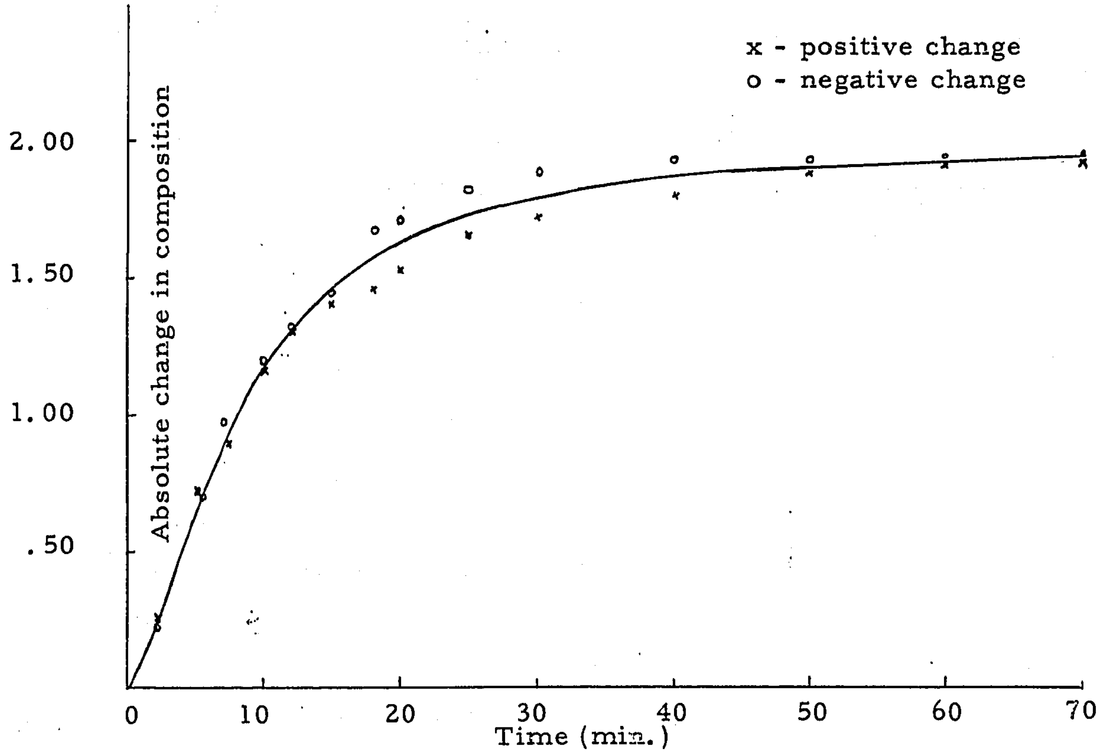


Fig. 4.4.a. Response of 7th Plate
for a 10% Step Change in Reflux.

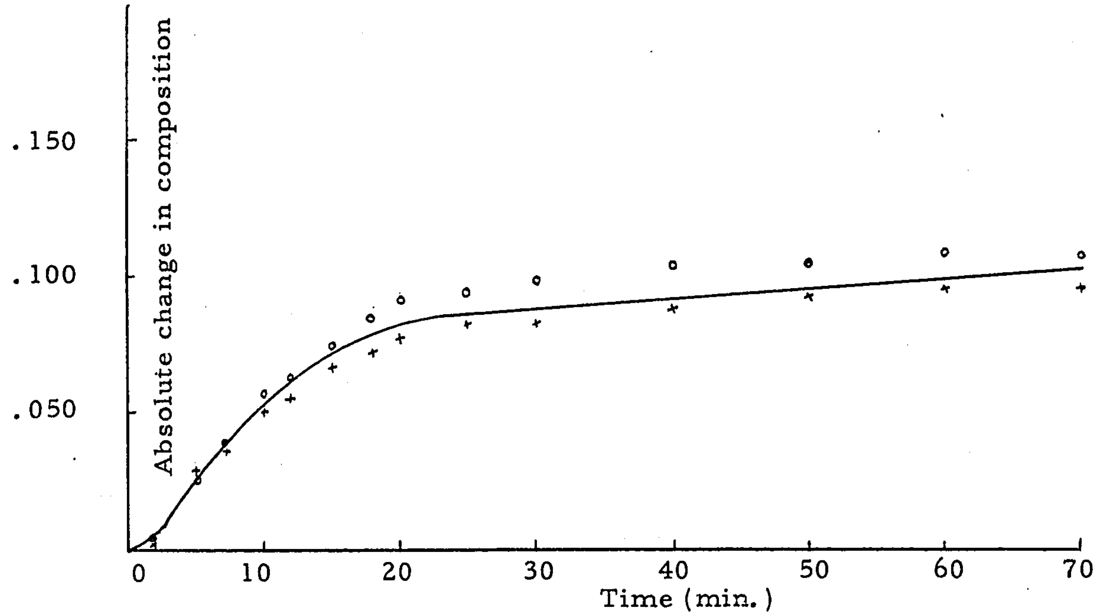


Fig. 4.4.b. Response of 2nd Plate
for a 10% Step Change in Reflux.

Tables IV i, j, k, l. The behaviour of the plates is shown in Figs. 4.6 a.b. It can be shown theoretically that plate efficiency of the column increases with the decrease in steam pressure and vice versa.

iv) Determination of the Open-Loop Transfer Functions of the Plates by Digital Computer.

It was found from the shape of the curves that open-loop transfer function of either plate can be approximated by $y(p) = \frac{e^{-pt}}{1+pt}$ for all the three tests. Where e^{-pt} is a pure delay and $\frac{1}{1+pt}$ is a first order lag. Program for the digital computer was prepared and the time constants of plates for all the three tests determined by the least square error criterion. The details of the program are given in Appendix II. The time constants of the plates are given below:

COMPOSITION TEST:

7th Plate: t_{c_7} = 0.7 min., T_{c_7} = 8.5 min.

2nd Plate: t_{c_2} = 0.85 min., T_{c_2} = 11.1 min.

REFLUX TEST:

7th Plate: t_{r_7} = 0.5 min., T_{r_7} = 10.6 min.

2nd Plate: t_{r_2} = 0.6 min., T_{r_2} = 13.5 min.

REBOIL TEST:

7th Plate: t_{s_7} = 0.2 min., T_{s_7} = 5.9 min.

2nd Plate: t_{s_2} = 0.2 min., T_{s_2} = 6.0 min.

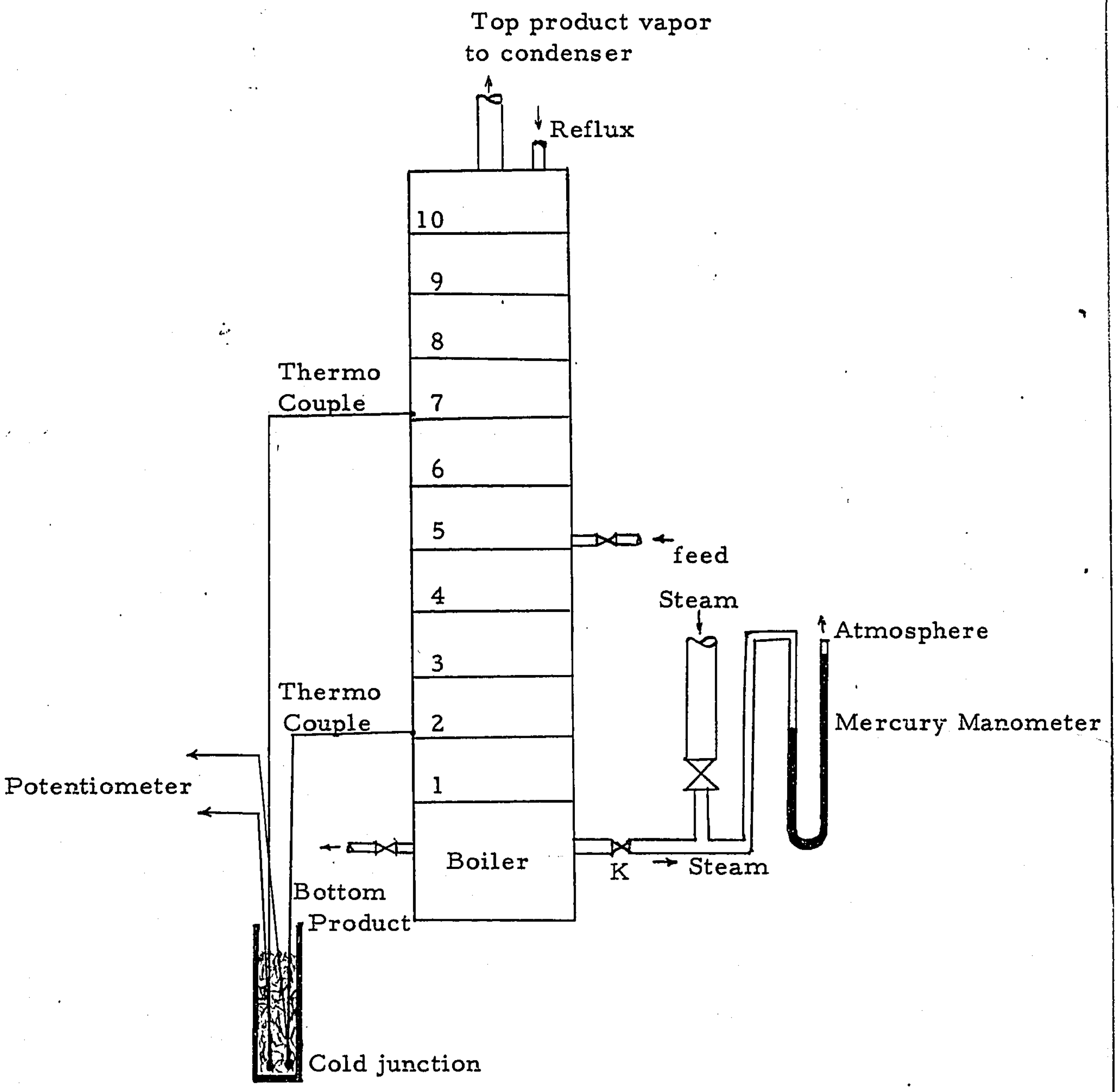


Fig. 4.5. Scheme for Imposing Reboil Test.

TABLE IV-i

Reboil Test

7th Plate +10% Change

Transmission delay neglected.

Time (min.)	Potentiometer Reading (mv)	Temperature °F	Absolute Change in Temperature	Composition % methanol	Absolute Change in Composition
0	3.8415	164.400	0.000	78.100	0.000
2	3.8515	164.775	0.375	77.600	0.500
5	3.8740	165.550	1.150	76.575	1.525
7	3.8808	165.900	1.500	76.100	2.000
10	3.8875	166.025	1.625	75.930	2.170
12	3.8897	166.075	1.675	75.840	2.250
15	3.8903	166.125	1.725	75.780	2.320
18	3.8923	166.175	1.775	75.720	2.380
20	3.8940	166.250	1.850	75.625	2.475
25	3.8949	166.277	1.877	75.592	2.508
30	3.8955	166.300	1.900	75.550	2.550
40	3.8960	166.325	1.925	75.530	2.570
50	3.8965	166.350	1.950	75.500	2.600
60	3.8965	166.350	1.950	75.500	2.600

TABLE IV-j

Reboil Test

7th Plate -10% Change

Transmission delay neglected.

Time (min.)	Potentiometer Reading (mv)	Temperature ^{o}F	Absolute Change in Temperature	Composition % methanol	Absolute Change in Composition
0.	3.8415	164.400	0.000	78.100	0.000
2	3.8325	164.100	0.300	78.500	0.400
5	3.8105	163.320	1.080	79.550	1.450
7	3.8035	163.100	1.300	79.870	1.770
10	3.7960	162.825	1.575	80.225	2.125
12	3.7947	162.755	1.645	80.300	2.200
15	3.7926	162.710	1.690	80.370	2.270
18	3.7900	162.625	1.775	80.500	2.400
20	3.7865	162.525	1.875	80.600	2.500
25	3.7860	162.500	1.900	80.630	2.530
30	3.7858	162.491	1.909	80.634	2.534
40	3.7855	162.480	1.920	80.650	2.550
50	3.7855	162.480	1.920	80.650	2.550

TABLE IV-k

Reboil Test

2nd Plate +10% Change

Transmission delay neglected.

Time (min.)	Potentiometer Reading (mv)	Temperature ^{o}F	Absolute Change in Temperature	Composition % methanol	Absolute Change in Composition
0	4.3702	182.0260	0.0000	52.9700	0.0000
2	4.3752	182.2000	0.1740	52.7120	0.2570
5	4.3872	182.5920	0.5660	52.1250	0.8450
7	4.3887	182.6430	0.6170	52.0500	0.9200
10	4.3912	182.7280	0.7020	51.9120	1.0570
12	4.3924	182.7620	0.7360	51.8620	1.0570
15	4.3935	182.8000	0.7740	51.8050	1.1650
18	4.3947	182.8430	0.8190	51.7370	1.2320
20	4.3958	182.8800	0.8540	51.6870	1.2820
25	4.3961	182.8870	0.8610	51.6750	1.2950
30	4.3964	182.9010	0.8750	51.6500	1.3200
40	4.3967	182.9120	0.8860	51.6480	1.3220
50	4.3968	182.9150	0.8890	51.6370	1.3320
60	4.3969	182.9190	0.8930	51.6250	1.3450

TABLE IV-1

Reboil Test

2nd Plate -10% Change

Transmission delay neglected.

Time (min.)	Potentiometer Reading (mv)	Temperature °F	Absolute Change in Temperature	Composition % methanol	Absolute Change in Composition
0	4.3704	182.0370	0.0000	52.9500	0.0000
2	4.3664	181.9000	0.1370	53.1620	0.2120
5	4.3554	181.5370	0.5000	53.7000	0.7500
7	4.3529	181.4500	0.5870	53.8570	0.8870
10	4.3504	181.3670	0.6700	53.9620	1.0120
12	4.3489	181.3190	0.7180	54.0370	1.0870
15	4.3479	181.3000	0.7370	54.0500	1.1000
18	4.3463	181.2340	0.8030	54.1620	1.2120
20	4.3452	181.2000	0.8370	54.2000	1.2500
25	4.3448	181.1840	0.8530	54.2230	1.2730
30	4.3447	181.1810	0.8560	54.2250	1.2750
40	4.3446	181.1720	0.8650	54.2370	1.2870
50	4.3444	181.1690	0.8680	54.2410	1.2910
60	4.3443	181.6700	0.8700	54.2430	1.2930

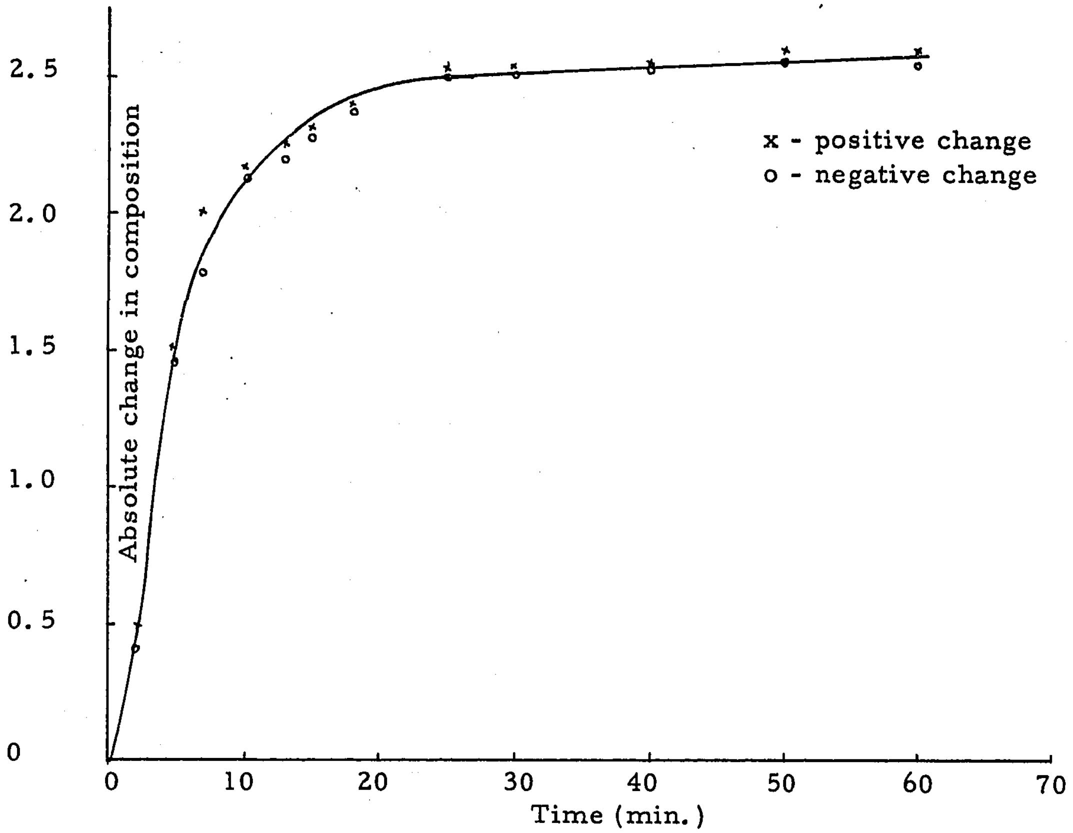


Fig. 4.6.a. Response of 7th Plate for 10% Change in Reboil.

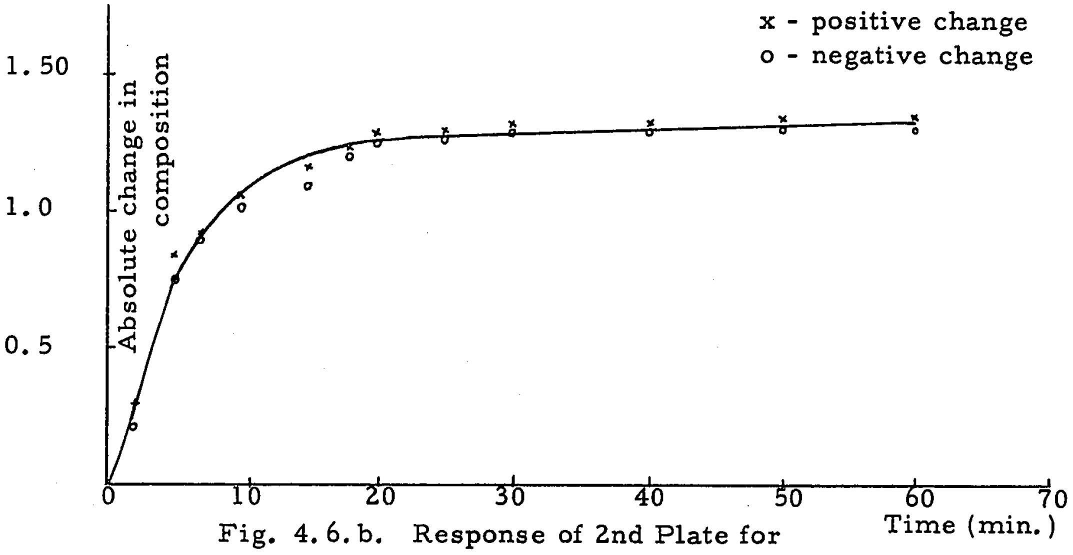


Fig. 4.6.b. Response of 2nd Plate for 10% Change in Reboil.

CHAPTER V

i) Analog Simulations.

a) Open-Loop Transfer Functions of the Plates:

The shape of the dynamic responses of the plates and their respective time constants, determined in Chapter IV, can now be used for analog simulation purpose. Since the transmission delay in the pipe and the transport delay in the plates are non-interacting, they can be treated as simple exponential lags. The detailed treatment of simulation is given in Appendix III.

Due to change in composition:

7th Plate: $$\frac{1}{(1+3.6s)(1+8.5s)} \times \frac{.78}{5.5}$$

2nd Plate: $$\frac{1}{(1+3.95s)(1+11.1s)} \times \frac{1.27}{5}$$

Due to change in reflux:

7th Plate: $$\frac{1}{(1+4.5s)(1+10.6s)} \times \frac{1.95}{9.5}$$

2nd Plate: $$\frac{1}{(1+5.2s)(1+13.5s)} \times \frac{.102}{9.5}$$

Due to change in reboil:

7th Plate: $$\frac{1}{(1+.2s)(1+5.9s)} \times \frac{2.575}{1}$$

2nd Plate: $$\frac{1}{(1+.2s)(1+6.0s)} \times \frac{1.325}{1}$$

b) Temperature Transmitters:

The time constants of the temperature transmitters are of the order of one second and have negligible effect on the performance of the present system, which has its time constant in minutes. With this simplification, the temperature transmitters are treated as simple gain devices. The details are given in Appendix III.

c) Control Valves:

The control valves for reflux and steam both have linear characteristics and their time constants are of the order of the second, which are negligible as compared to the time constants of the plates. Hence, the control valves are simulated as simple gain devices. The details are given in Appendix III.

d) Controller:

The penmatic controller used in the control loop, has proportional plus integral modes. The transfer function of the controller can be written as

$$T_c(t) = K\left[1+\frac{1}{T_i}\int dt\right]$$

The details are given in Appendix III.

ii) Scheme for the Automatic Control of the Composition of the Column Employing one Manipulated Variable i. e. Reflux.

The block diagram for one manipulated variable control is given below:

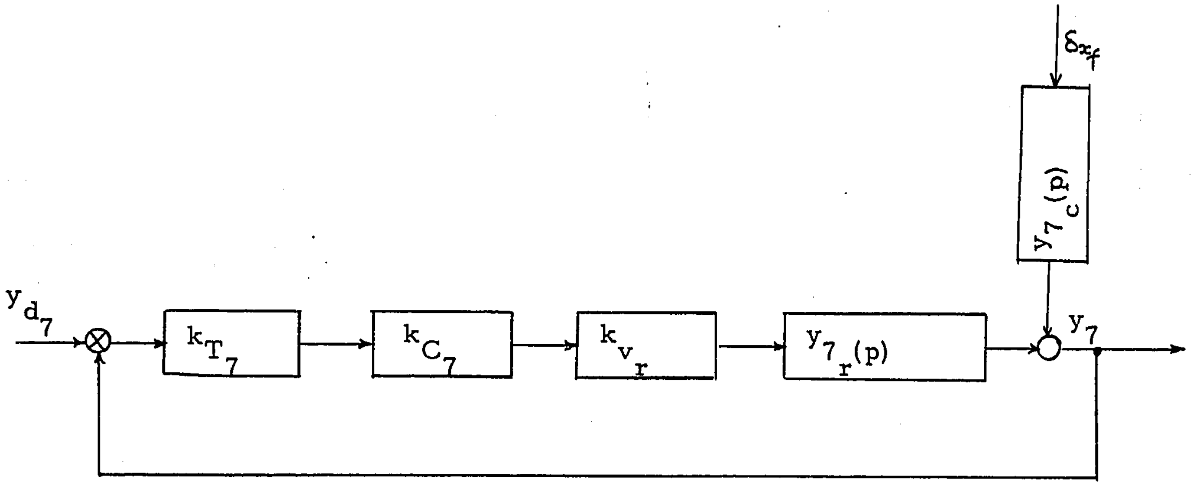


Fig. 5.1.* Block Diagram of the Scheme for the Control of the Distillation Column Employing Reflux as Manipulated Variable.

The analog simulation of the above system including the scheme to obtain integral of the squared error is given in Appendix III. In the simulation, the actual amplitude is scaled down ten times and one minute of real time of the system is represented by one second of computer time. The scheme for potentiometer settings is given in Appendix III. The responses of the output compositions and the reflux valve for different values of gain and integration time constants of the controller resulting from 6 percent change in the feed composition are given in Figs. 5.2 a, b, c, d, e, f.

iii) Determination of the Optimum Parameters of the Controller.

The relative decrease in the magnitude of $\int_0^\infty e^2 dt$ for different sets of the gain and the time constants of integration of the controller is shown in Tables V, a, b. Fig. 5.3-5.5 show the relative

---

* The blocks of the above diagram are defined on page 124.

TABLE V-a

Time Constant of Integration of the Controller = 5 minutes

No. of observations	Gain K	$\int_0^\infty e^2\,dt$
1	.50	3.70
2	1.00	1.78
3	1.50	1.23
4	2.00	0.84
5	2.50	0.64
6	3.50	0.41
7	5.00	0.23
8	6.00	0.16
9	7.00	0.13
10	8.00	0.08
11	9.00	0.07
12	10.00	0.05
13	12.00	0.05
14	15.00	0.03
15	20.00	0.02
16	30.00	0.03

TABLE V-b

No. of observations	Integration time constant T_i(min.)	$\int_0^\infty e^2\,dt$ for K=10	$\int_0^\infty e^2\,dt$ for K=20
1	3	.22	unstable
2	5	.056	.019
3	10	.073	.019
4	20	.094	.020
5	50	.160	.027

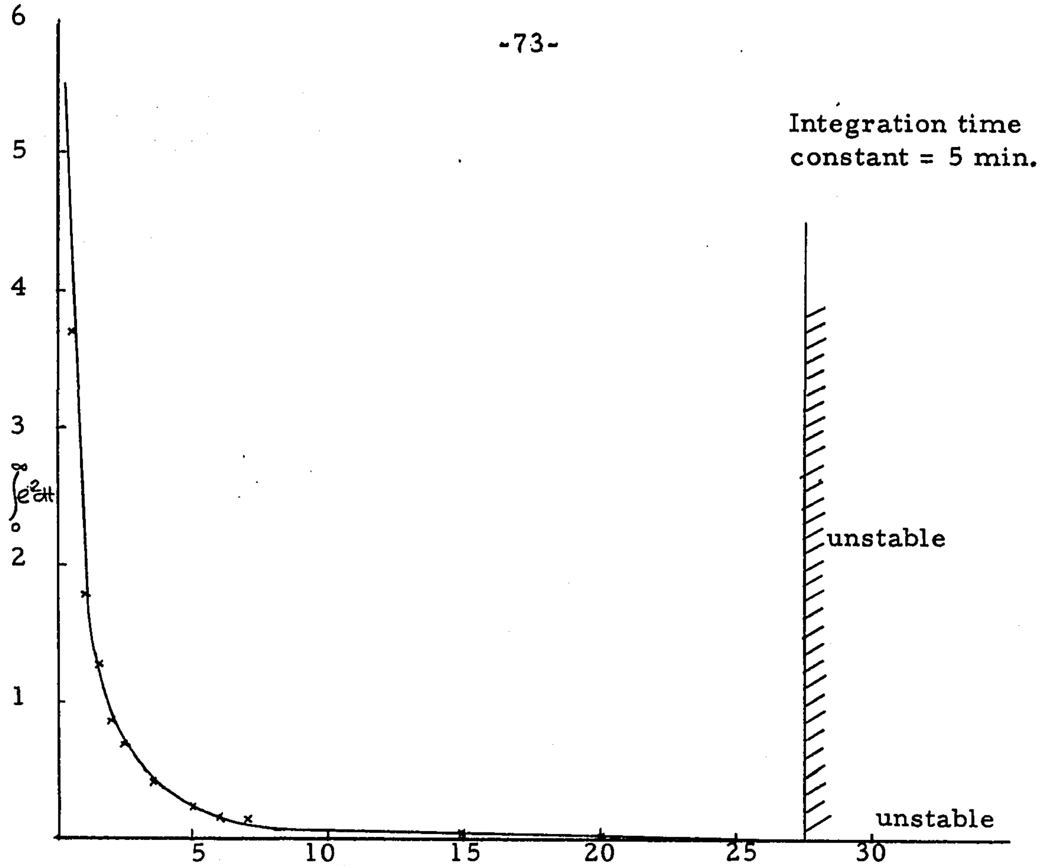


Fig. 5.3. Plot of $\int_0^\infty e^2 dt$ for Different Values of Gain at T_{i7}=5 min.

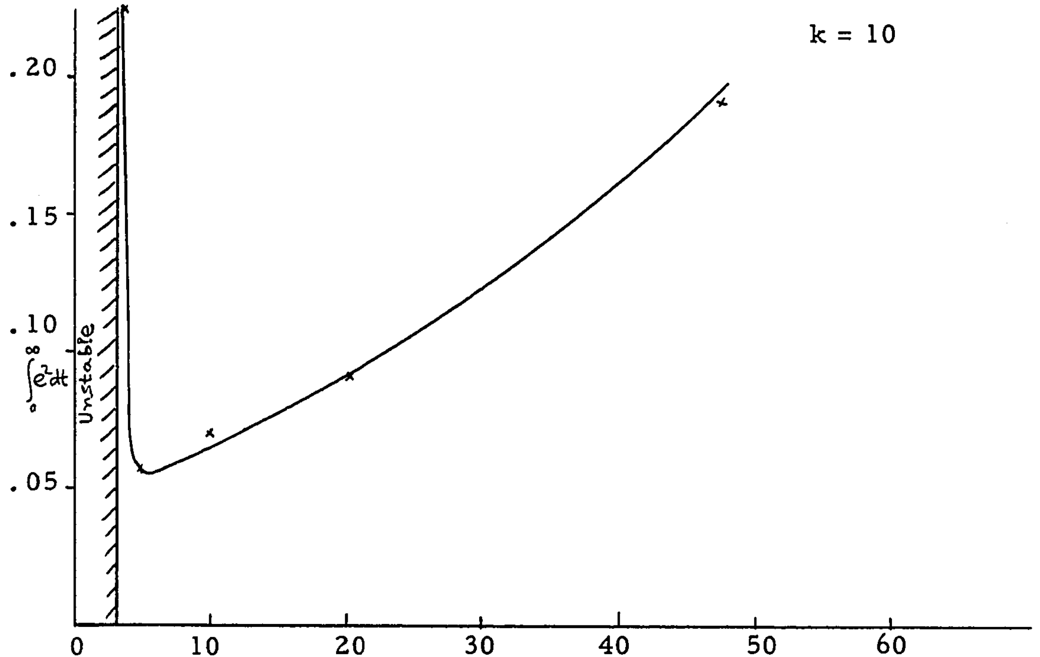


Fig. 5.4. Plot of $\int_0^\infty e^2 dt$ for Different Values of T_{i7} at K = 10.

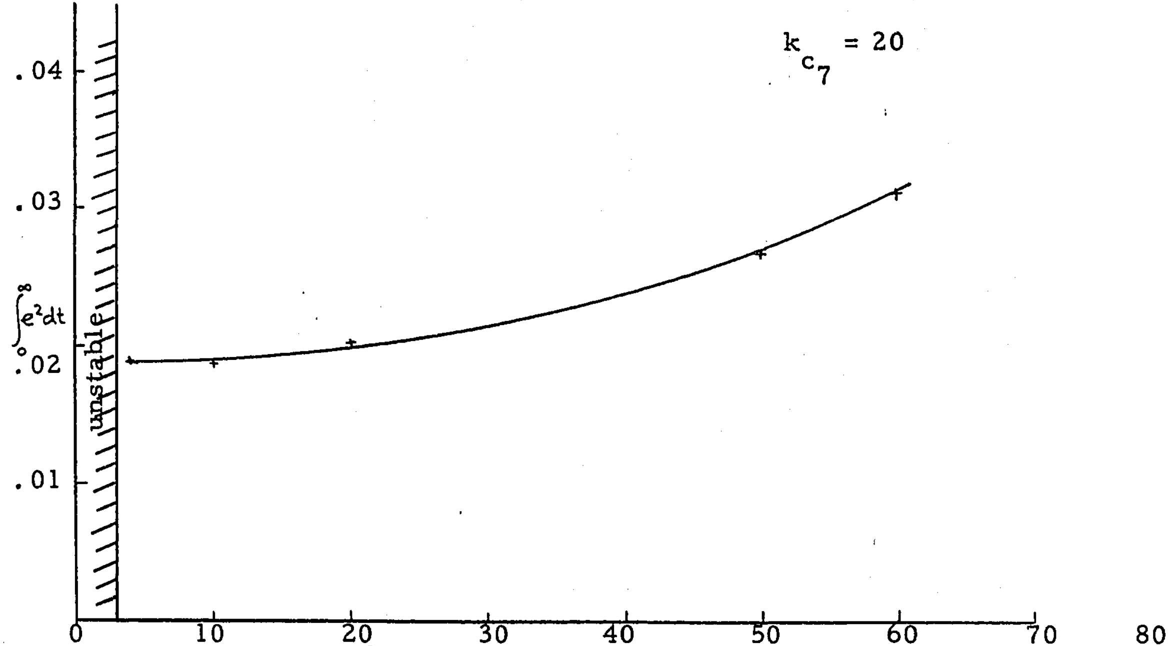


Fig. 5. 5. Plot of $\int_0^\infty e^2 dt$ for Different Values of T_{i7} at K = 20.

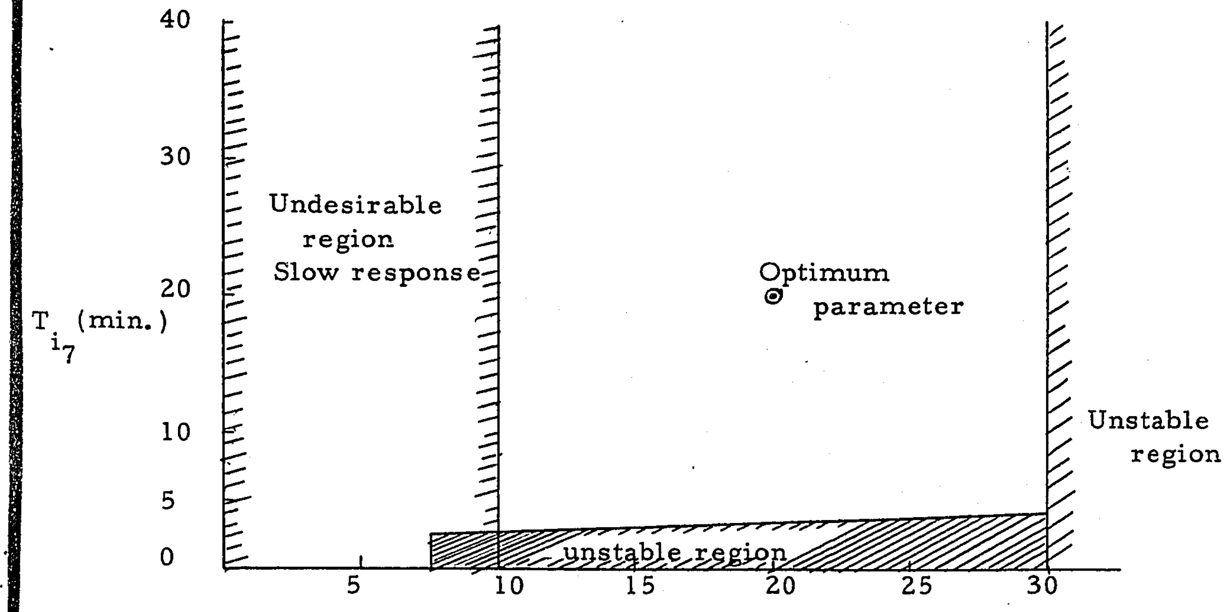


Fig. 5. 6. Allowable Regions of the Controller for the Operation.

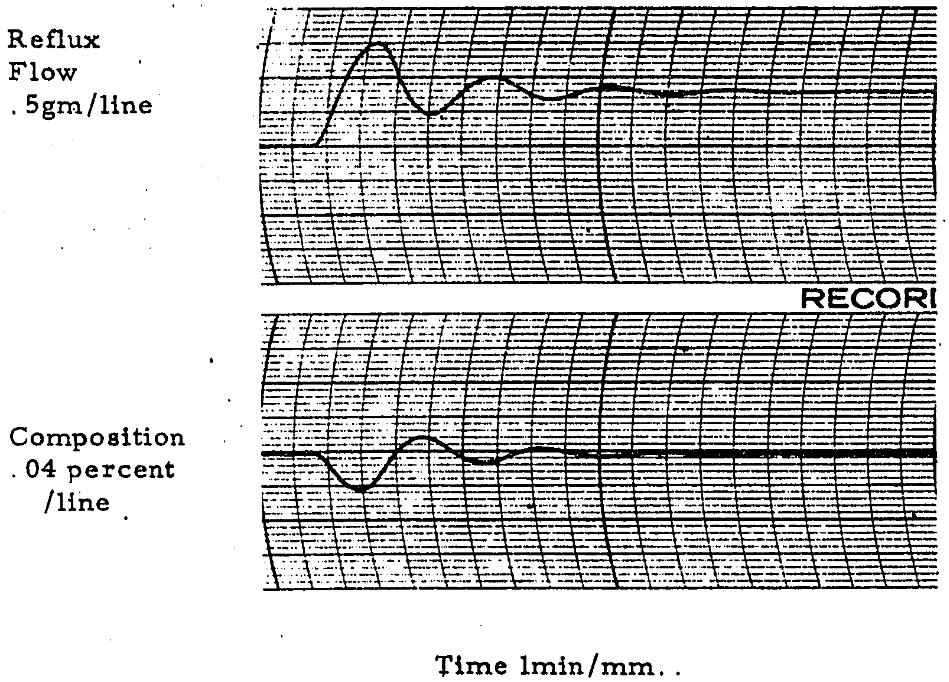
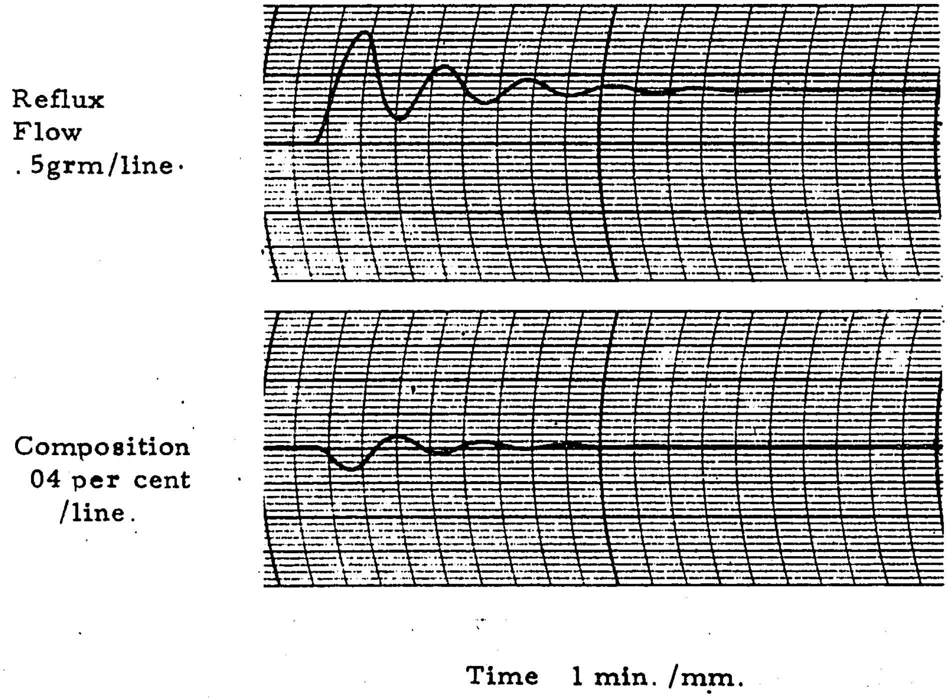


Fig. 5.2 a Responses of reflux valve and composition at plate -7 for 6 per cent disturbance in feed composition. (k_{c_7} = 5 , T_{c_7} = 5 min).



5.2. b. Responses of reflux valve and composition at plate-7 for 6 per cent disturbance in feed composition (k_{c_7} = 10, T_{c_7} = 5 min.).

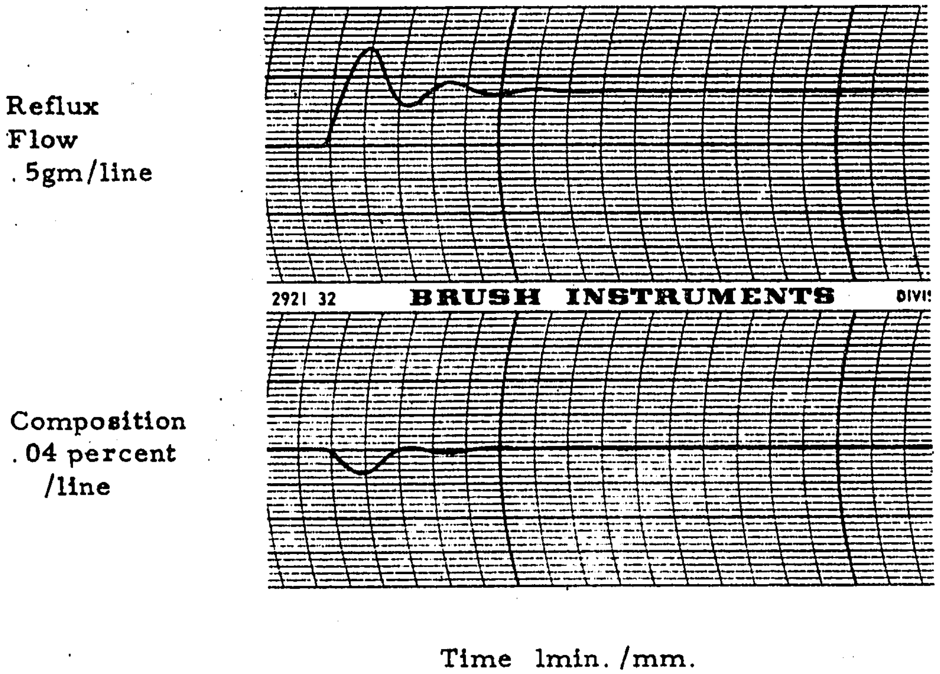


Fig. 5.2.c Response of reflux valve and composition at plate-7 for 6 percent disturbance in feed composition. (k_{c_7} = 10, T_{c_7} = 10 min.).

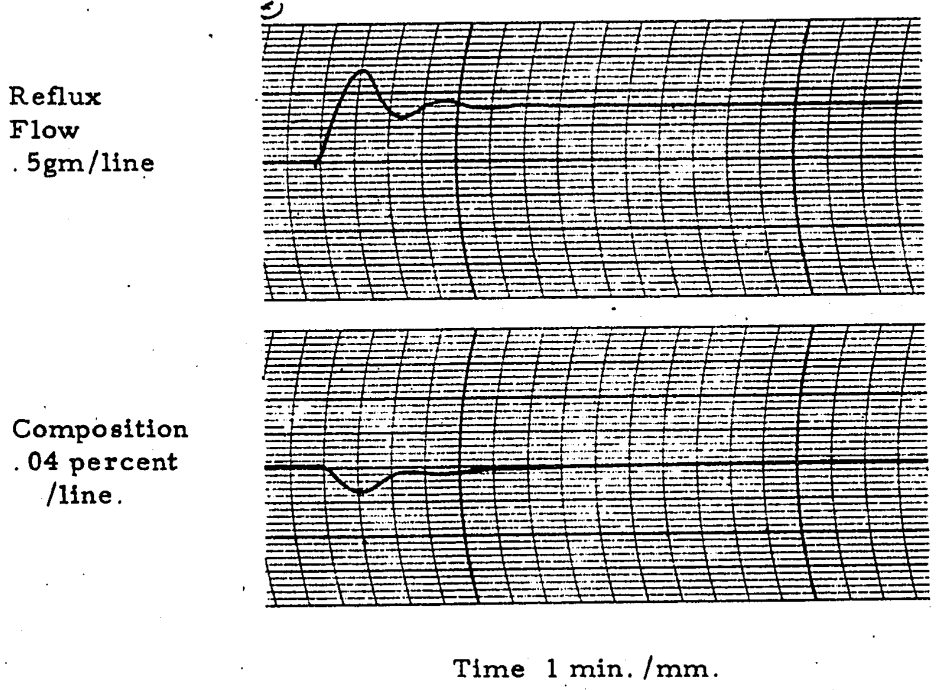


Fig. 5.2.d. Responses of reflux valve and composition at plate-7 for 6 percent disturbance in feed composition. (k_{c_7} = 10, T_{c_7} = 20 min.).

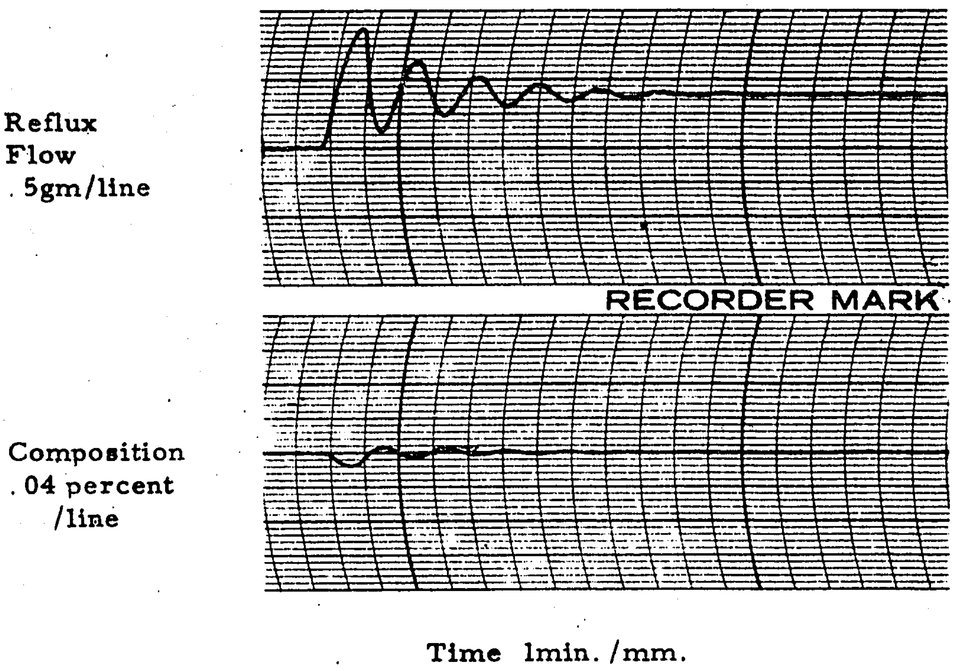


Fig. 5.2.e. Responses of reflux valve and composition at plate-7 for 6 percent disturbance in feed composition (k_{c_7} = 20, T_{i_7} = 5 min.).

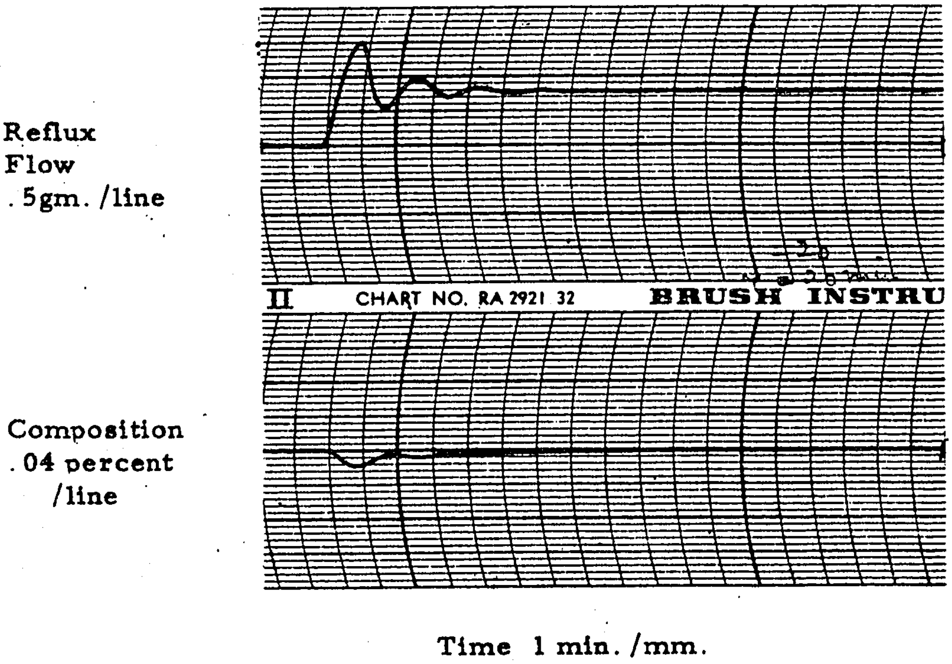


Fig. 5.2.f. Responses of reflux valve and composition at plate-7 for 6 percent disturbance in feed composition (k_{c_t} = 20, T_{i_7} = 20min.).

change in the integral of the square of the error for different combinations of the controller parameters. Fig. 5.6 shows the allowable région for the operation and the optimum parameters of the controller. At the optimum setting of the controller parameters ($k = 20$, $T_{i7} = 20$ min.), the variations in the composition of plate-7 for ± 6 percent change in the feed composition was ± 0.1 percent and system assumed its steady state in 25 minutes. The quality of the top product was hardly affected with such small change, because due to the control action, this change is dissipated within the column before it reaches the top plate.

iv) Scheme for the Automatic Control of the Composition of the Column Employing two Manipulated Variables (Reflux and Reboil).

The block diagram for two manipulated variable control is given below:

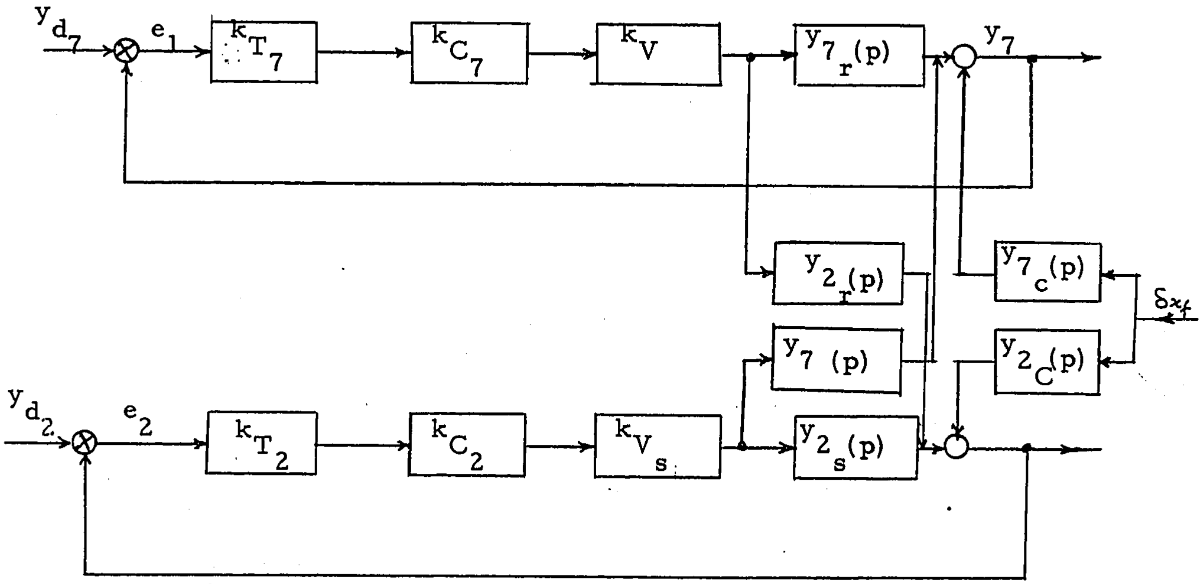


Fig. 5.7.* Block Diagram of the Scheme for the Control of the Distillation Column Employing Reflux and Reboil as M. V.

* The blocks of the above diagram are defined on page 124.

The analog simulation of the above system including the scheme to obtain the integral of the square of the error is given in Appendix III. The variables are scaled down ten times in amplitude and one second of the computer time represents one minutes of the real time. The potentiometer settings are given in Appendix III. The responses of the output compositions of plates "7" and "2" for different combination of the gain and integration time constants of the controller resulting from 6 percentage change in the feed composition are given in Figs. 5.8 a, b, c, d, e, f.

v) Determination of the Optimum Parameters of the Controller.

The relative decrease in the magnitude of integral of the error squared for different sets of the gains and time constants of integration of the controller is shown in Table V-d, e, f. The optimum parameters resulting from these observations are:

$$k_{c_7} = 25, \quad K_{c_2} = 20, \quad T_{i_7} = 6 \text{ min.}, \quad T_{i_2} = 5 \text{ min.}$$

At the optimum values of parameters of the controllers, the maximum variation in the output composition of the plates "7" and "2" were 0.35 percent and .85 percent for a 6 percent change in feed composition. The steady state condition after this disturbance was reached in 25 and 65 minutes by plates "7" and "2" respectively.

vi) The Effect of Interaction on Control.

The negligible effect of the reflux on 2nd Plate reduced the interaction problem appreciably. The effect of a change in controller parameters of reboil loop on the response of 7th Plate was quite prominent

TABLE V-c

No. of observations	K_{c_7}'	K_{c_2}'	T_{i_7}' min.	T_{i_2}' min.	$\int_0^\infty (e_1^2 + e_2^2)dt$
1	5	5	5	5	262
2	7	7	7	7	171
3	10	10	10	10	96
4	12	12	12	12	68
5	15	15	15	15	56
6	20	20	20	20	40
7	25	25	25	25	30
8	30	30	30	30	31

TABLE V-d

No. of observations	K_{c_7}'	K_{c_2}'	T_{i_7}' min.	T_{i_2}' min.	$\int_0^\infty (e_1^2 + e_2^2)dt$
1	25	5	5	5	30
2	25	7	7	7	25
3	25	10	10	10	20
4	25	12	12	12	20
5	25	18	18	18	20
6	25	25	25	25	20
7	25	30	30	30	21

TABLE V-e

No. of observations	K_{c_7}	K_{c_2}	T_{i_7} min.	T_{i_2} min.	$\int_0^\infty (e_1^2 + e_2^2)dt$
1	25	20	3	5	unstable
2	25	20	4	5	24
3	25	20	5	5	20
4	25	20	6	5	19
5	25	20	8	5	23
6	25	20	10	5	24

TABLE V-f

No. of observations	K_{c_7}	K_{c_2}	T_{i_7} min.	T_{i_2} min.	$\int_0^\infty (e_1^2 + e_2^2)dt$
1	25	20	6	1	unstable
2	25	20	6	2	140
3	25	20	6	5	112
4	25	20	6	1	51
5	25	20	6	2	25
6	25	20	6	3	21
7	25	20	6	4	20
8	25	20	6	5	19
9	25	20	6	6	20

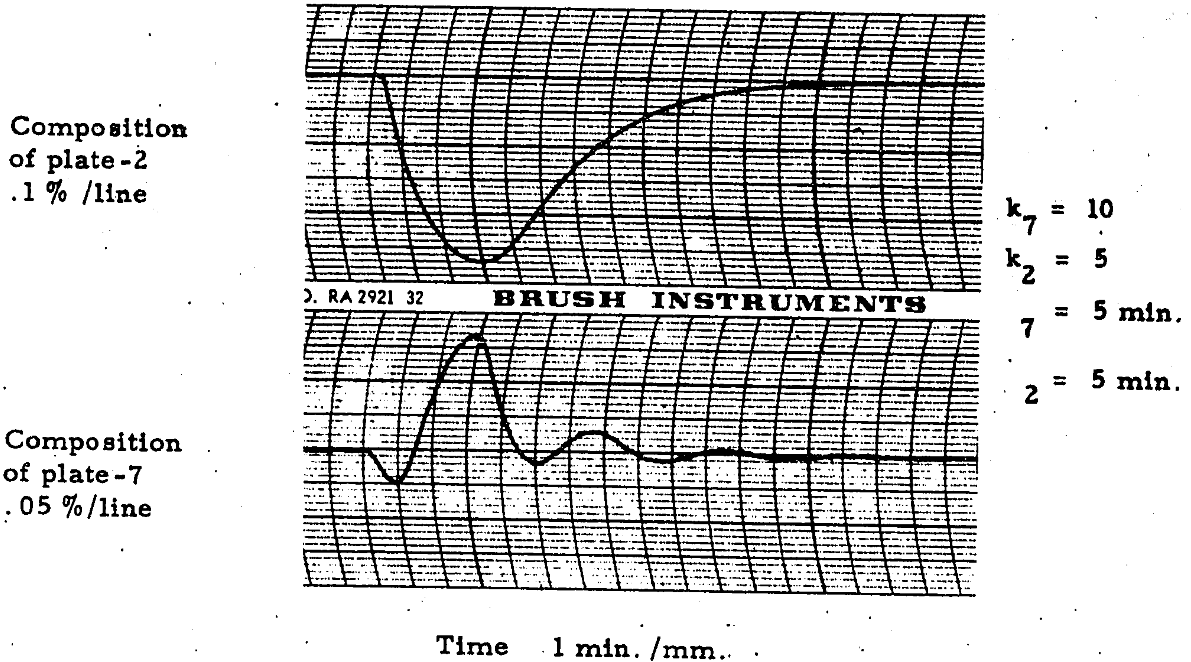


Fig. 5.8.a Responses of the compositions of plate '2' and '7' for 6 percent disturbance in feed composition (k_{c_7} = 10, k_{c_2} = 5, T_{i_7} = 5 min.. T_{i_2} = 5 min.)

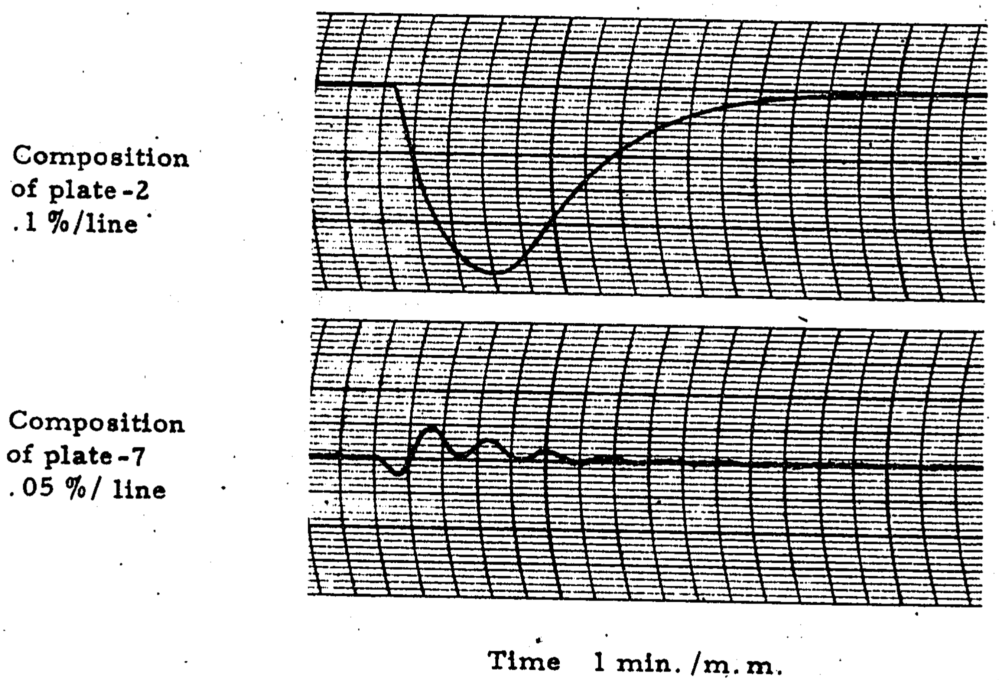


Fig. 5.8.b. Responses of the compositions of plates '2' and '7' for 6 percent disturbance in feed composition (k_{c_7} = 25, k_{c_2} = 5, T_{i_7} = 5 min, T_{i_2} = 5 min.).

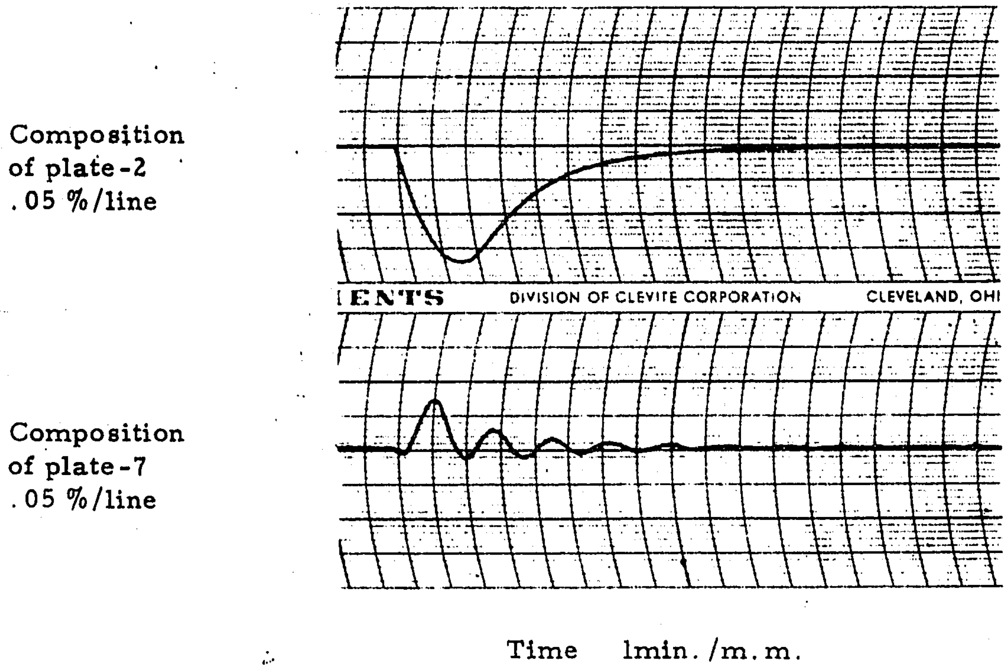


Fig. 5.8.c. Responses of the composition of plates '2' and '7' for 6 percent disturbance in feed composition (k_{c_7} = 25, k_{c_2} = 25, T_{i_7} = 5 min. T_{i_2} = 5 min.)

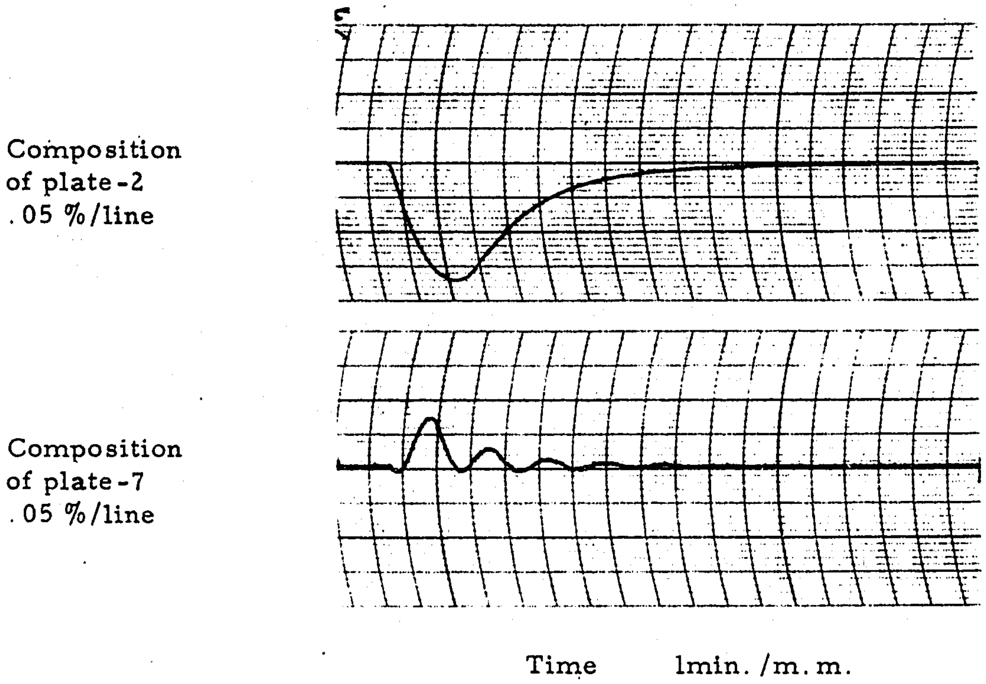


Fig. 5.8.d. Responses of the composition of plates '2' and '7' for 6 percent disturbance in feed composition (k_{c_7} = 25, k_{c_2} = 20, T_{i_7} = 6 min. T_{i_2} = 5 min.)

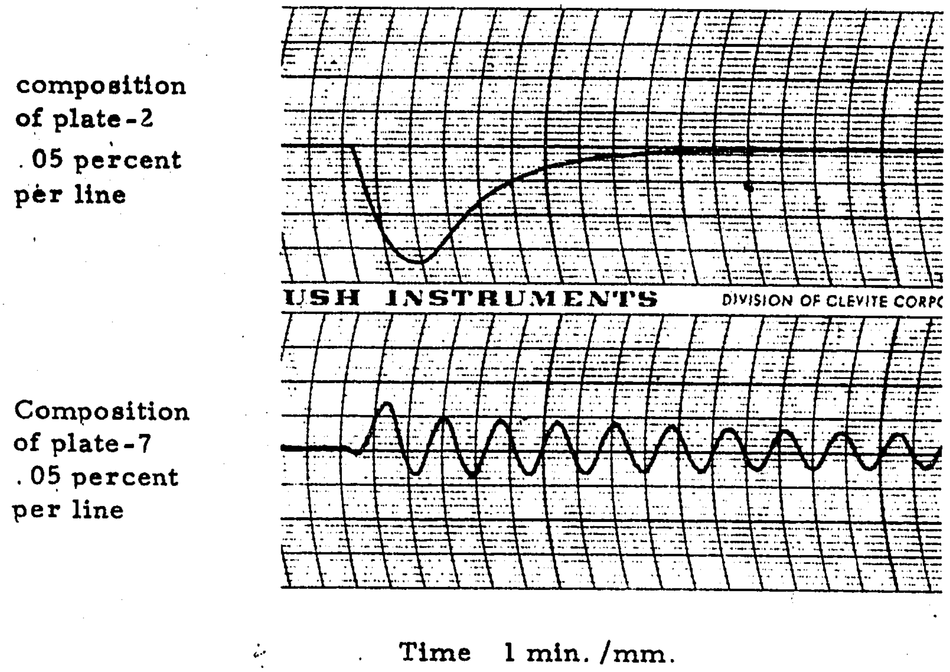


Fig. 5.8.e Responses of the compositions of 2 and 3 for 6 percent disturbance in the feed composition (k_{c_7} = 25, k_{c_2} = 20, T_{i_7} = 3 min. T_{i_2} = 5 min.).

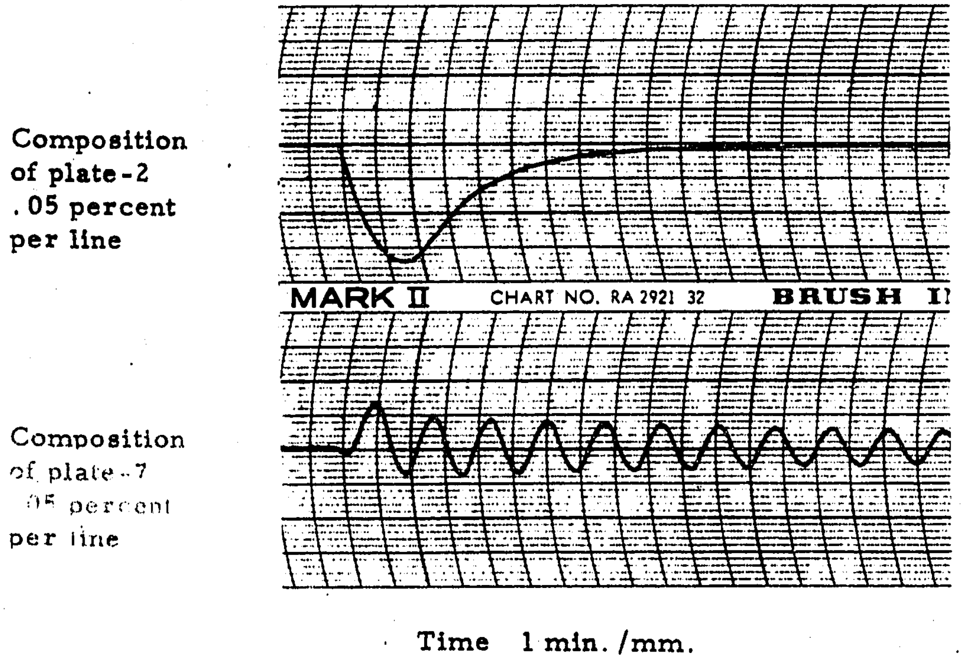


Fig. 5.8.f. Response of the composition of plates '2' and '7' for 6 percent disturbance in feed composition (k_{c_7} = 25, k_{c_2} = 20, T_{i_7} = 6 min., T_{i_2} = .1 min).

as appears in Fig. 5.8. At the optimum settings of the controllers, the maximum variation in the output of plates "7" and "2" was 0.35% and 0.85% respectively for a 6 percent change in the feed composition. Whereas in the first method, the maximum variation in the output was found to be 0.1 percent for the same disturbance. These comparatively large variations in the output compositions were the consequence of interaction between the two loops. However, at the optimum settings of the controller parameters, the interaction effect was minimum.

vii) Conclusions.

The one manipulated variable (reflux) control appears to be more attractive, since it has relatively better performance and is half as costly as two manipulated variables (reflux and reboil) control. In spite of its better performance and small cost, this method does not guarantee the desired composition distribution in the stripping section of the column. Especially in columns where reflux has comparatively small effect on stripping section, in the presence of disturbances, the variation in the composition distribution of the stripping section may be so great that column may lose its steady state condition.

Although, the initial cost of the two manipulated variable control is large, the reliability with which it controls the product compositions of the column is far more important to justify its use in practice. Moreover, since intermediate plates are employed for the control, the product compositions are very unlikely to be effected by slightly larger variations in the output compositions of the reference plates.

APPENDIX I

TABLE A.I-a

Feed Rotameter Calibration.

No.	Reading of Rotameter	Time taken to fill 100 cc. jar min.-sec.	Flow of H_2O gm./min.	Flow of 50:50 H_2O-CH_3OH (.897) sp. gravity
1	40	1-30.0	77.00	69.00
2	60	0-50.00	120.00	107.00
3	80	0-32.50	185.00	165.50
4	100	0-22.0	272.00	244.00
5	120	0-18.0	333.00	298.00
6	140	0-15.0	400.00	368.00
7	160	0-12.5	600.00	536.00
8	180	0-10.0	666.00	596.00
9	200	0- 9.0	750.00	672.00

TABLE A.I-b

Reflux Rotameter Calibration.

No.	Reading of Rotameter	Time taken to fill 100 c.c. jar min.-sec.	Flow of H_2O gm./min.	Flow of 93:7 $CH_3OH:H_2O$ sp. gravity .81
1	10	4-30.0	22.00	17.80
2	20	2-30.0	40.00	32.40
3	30	1-18.0	77.00	62.50
4	40	0-51.0	118.00	95.50
5	60	0-26.0	230.00	186.50
6	80	0-19.0	314.00	254.20
7	100	0-14.0	430.00	348.00
8	120	0-11.0	545.00	440.00
9	140	0- 8.5	705.00	570.00
10	160	0- 7.0	856.00	695.00

TABLE A.I-c

Product Rotameter Calibration.

No.	Reading of Rotameter	Time taken fill 100 c.c. jar min.-sec.	Flow of H_2O gm./min.	Flow of 93:70 $CH_3OH:H_2O$ sp. gravity .81 gm./min.
1	20	2-10.0	47.50	38.60
2	40	0-56.0	107.00	86.500
3	60	0-32.5	185.00	150.00
4	80	0-23.0	260.00	212.00
5	100	0-17.0	352.00	286.00
6	120	0-13.0	461.00	374.00
7	140	0-11.0	545.00	442.00

Fig. A.I.1 GRAPH

Rotameter Calibration

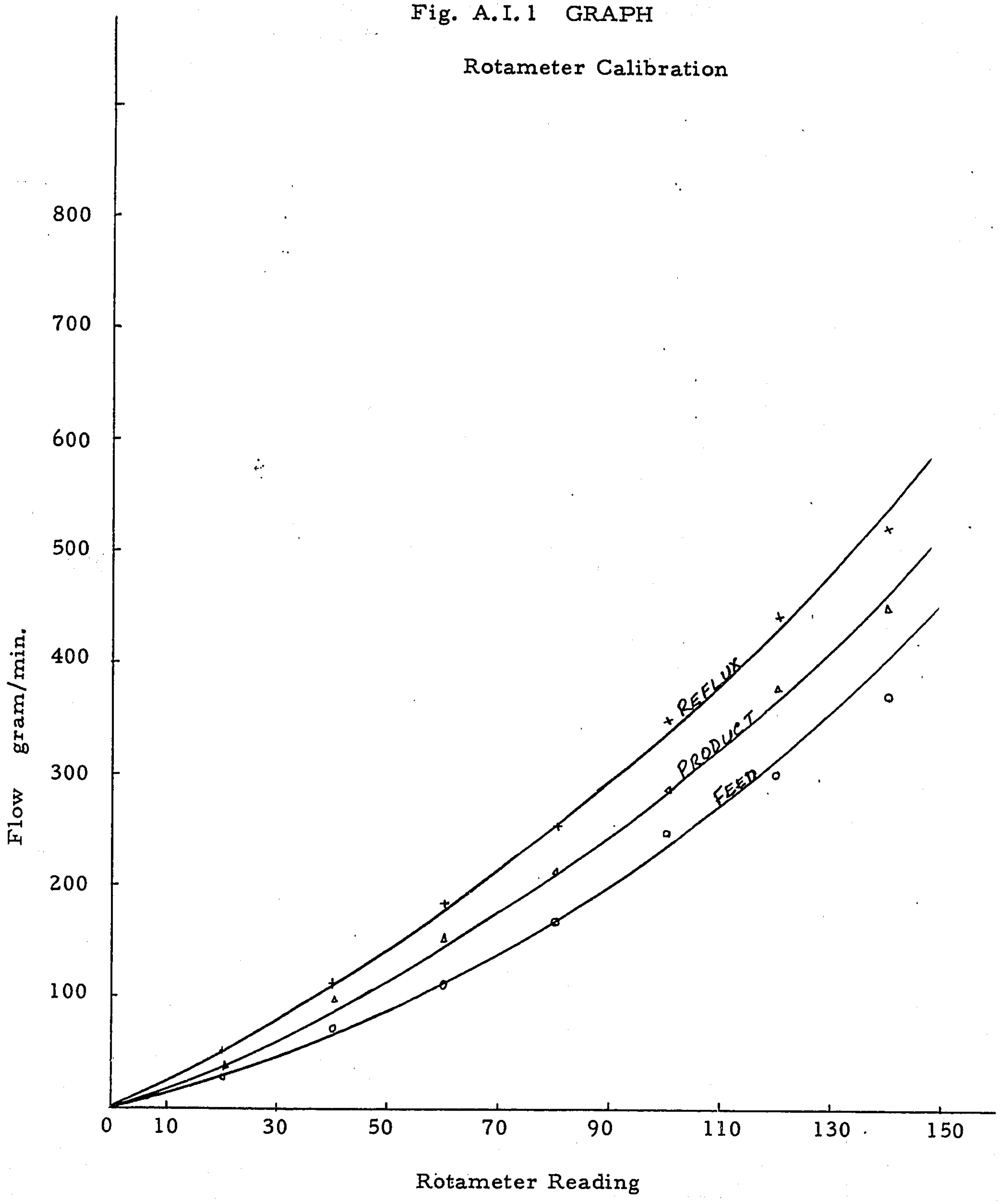


Fig. A.I.2.

EMF vs Temperature Curve for Iron-Constantan.

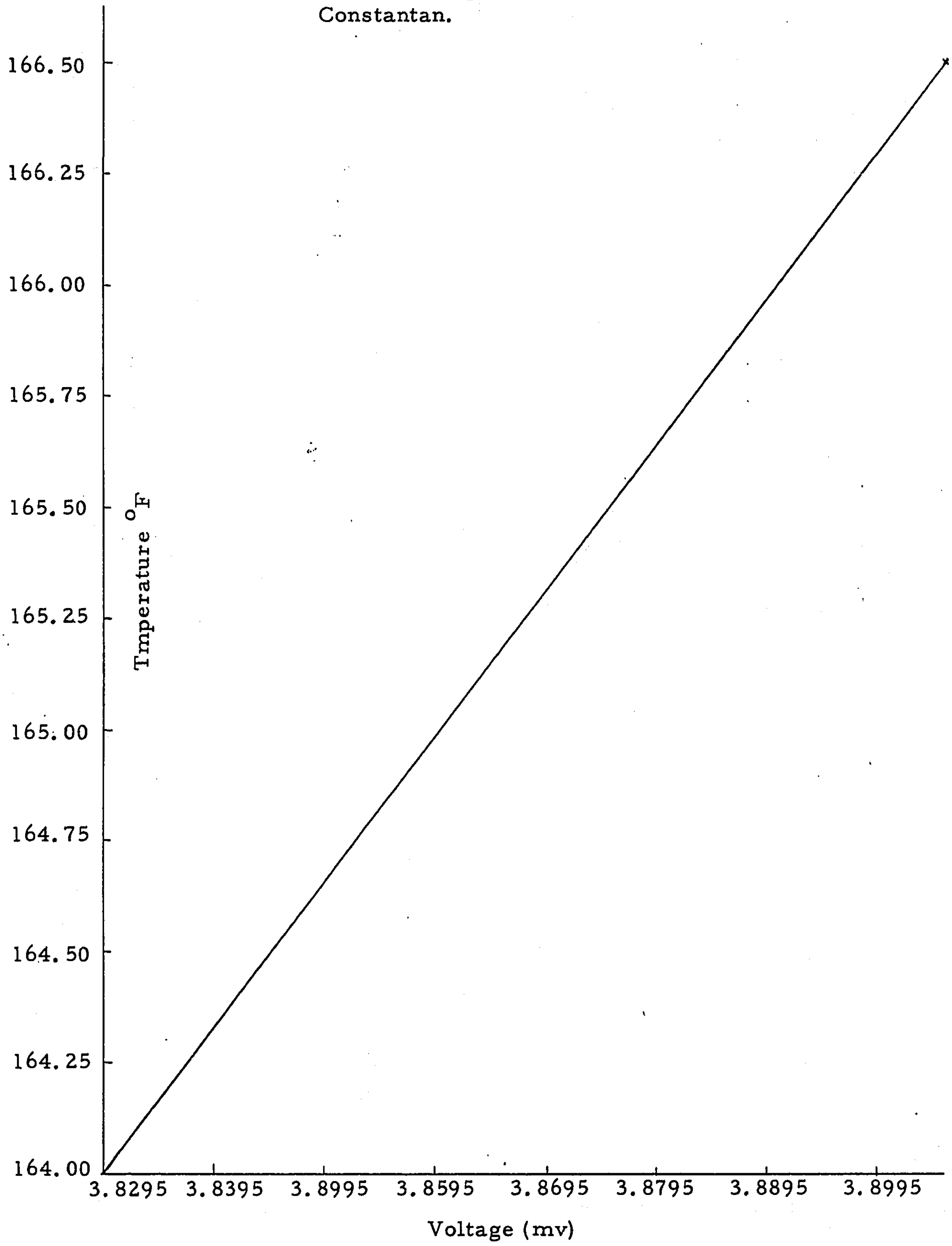
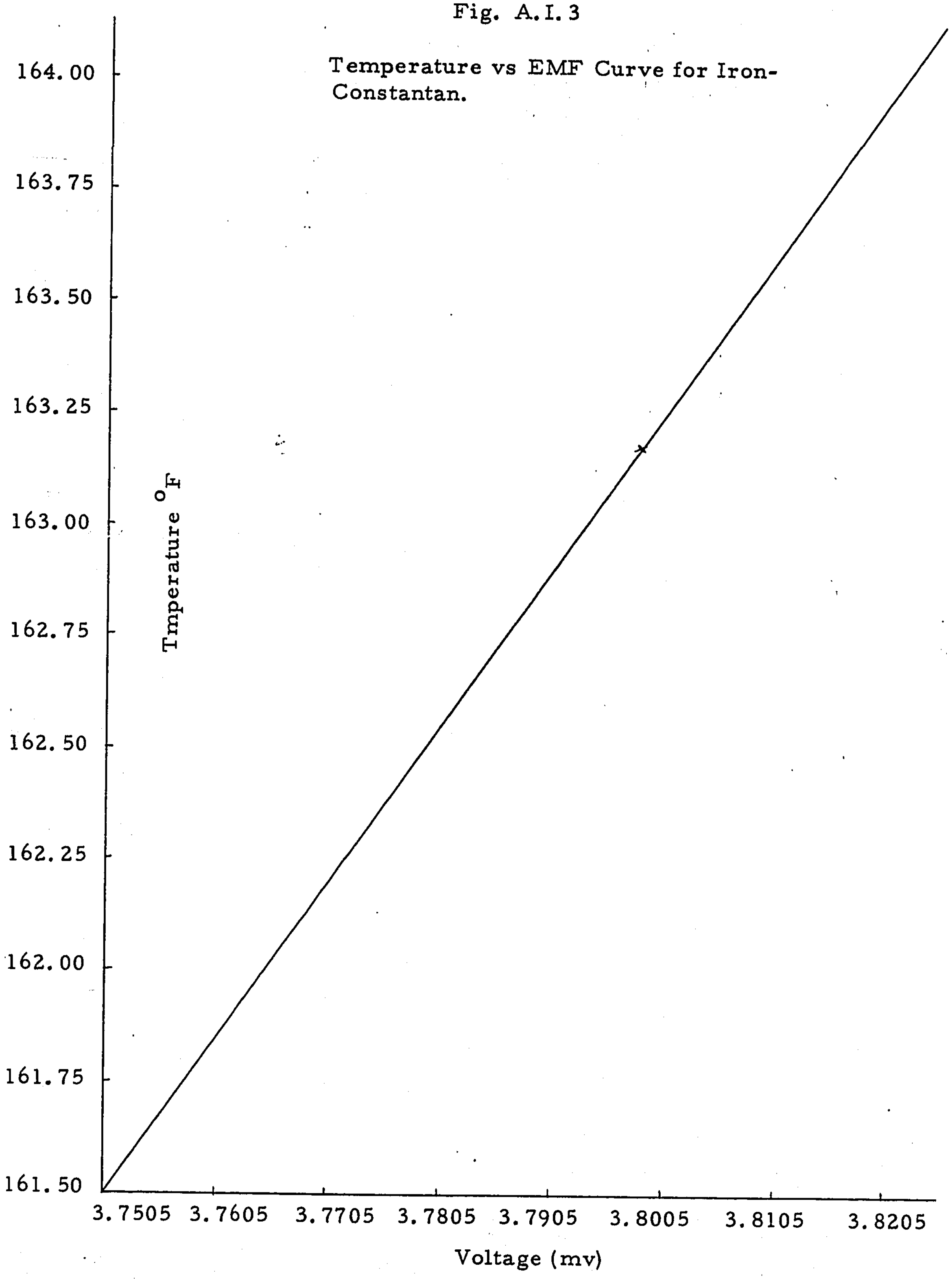


Fig. A.I.3

Temperature vs EMF Curve for Iron-Constantan.



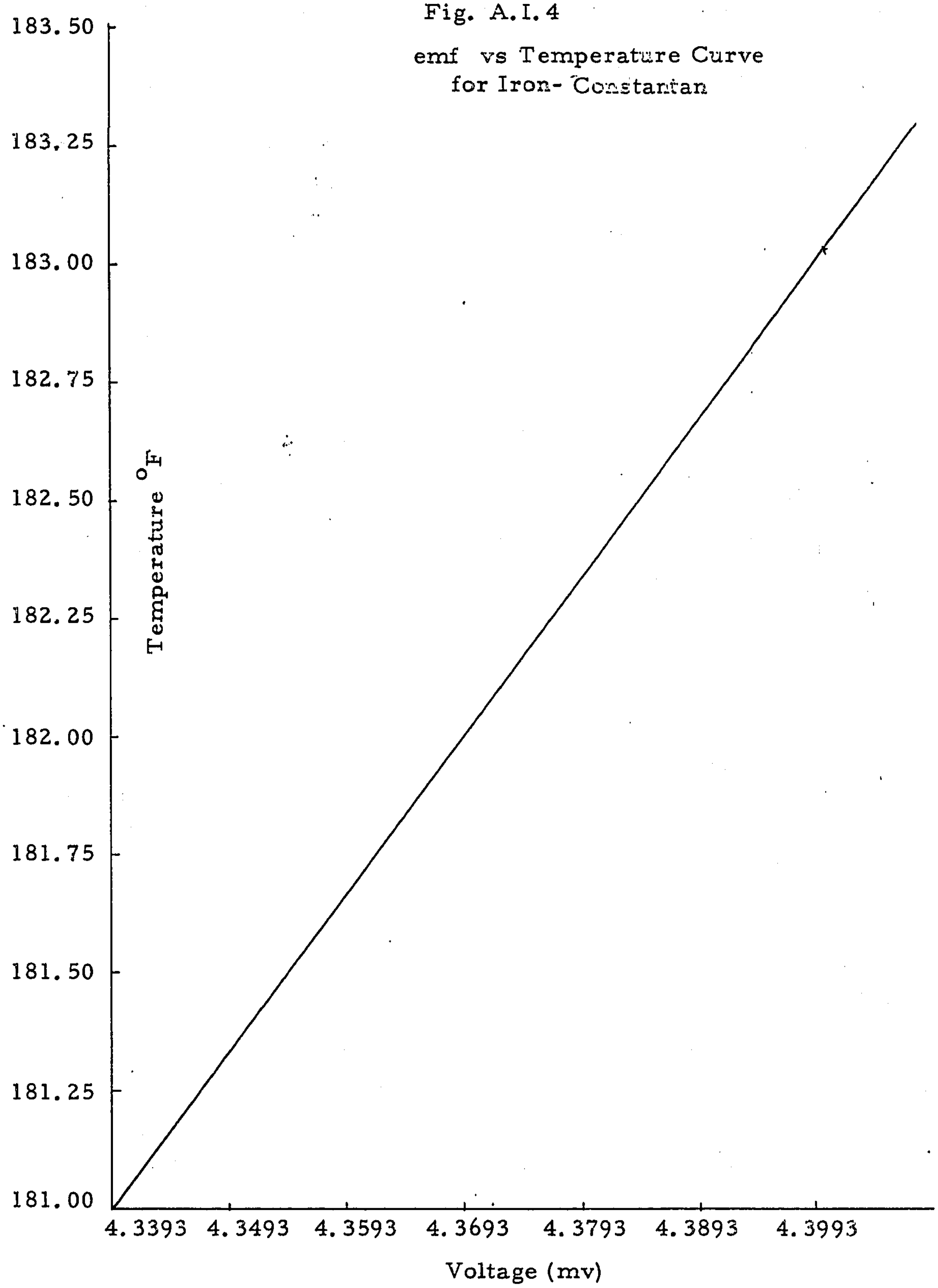


Fig. A.I.4

emf vs Temperature Curve for Iron- Constantan

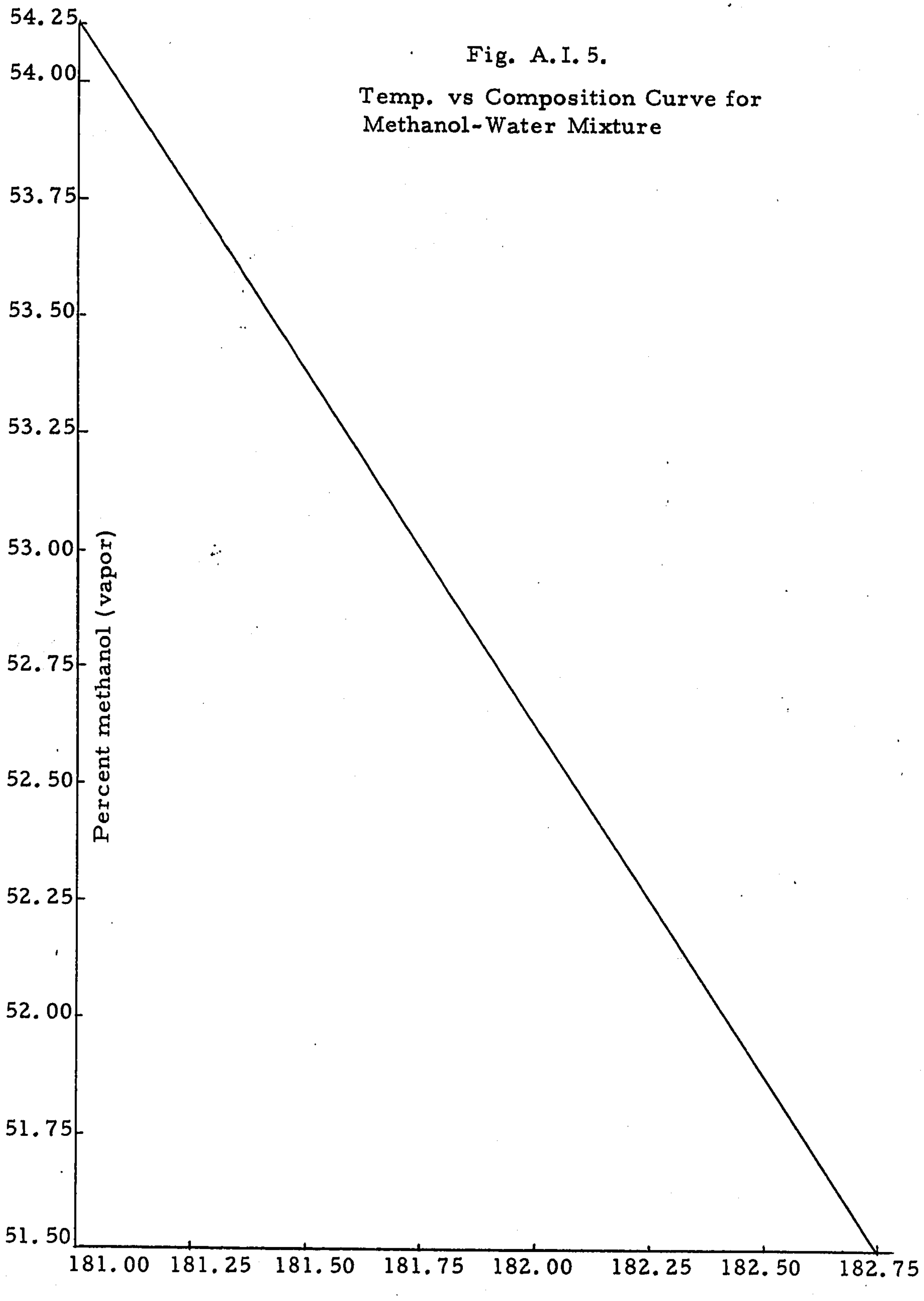


Fig. A.I.5.

Temp. vs Composition Curve for Methanol-Water Mixture

Fig. A.I. 6

Temp. vs Composition Curve for Methanol-Water Mixture.

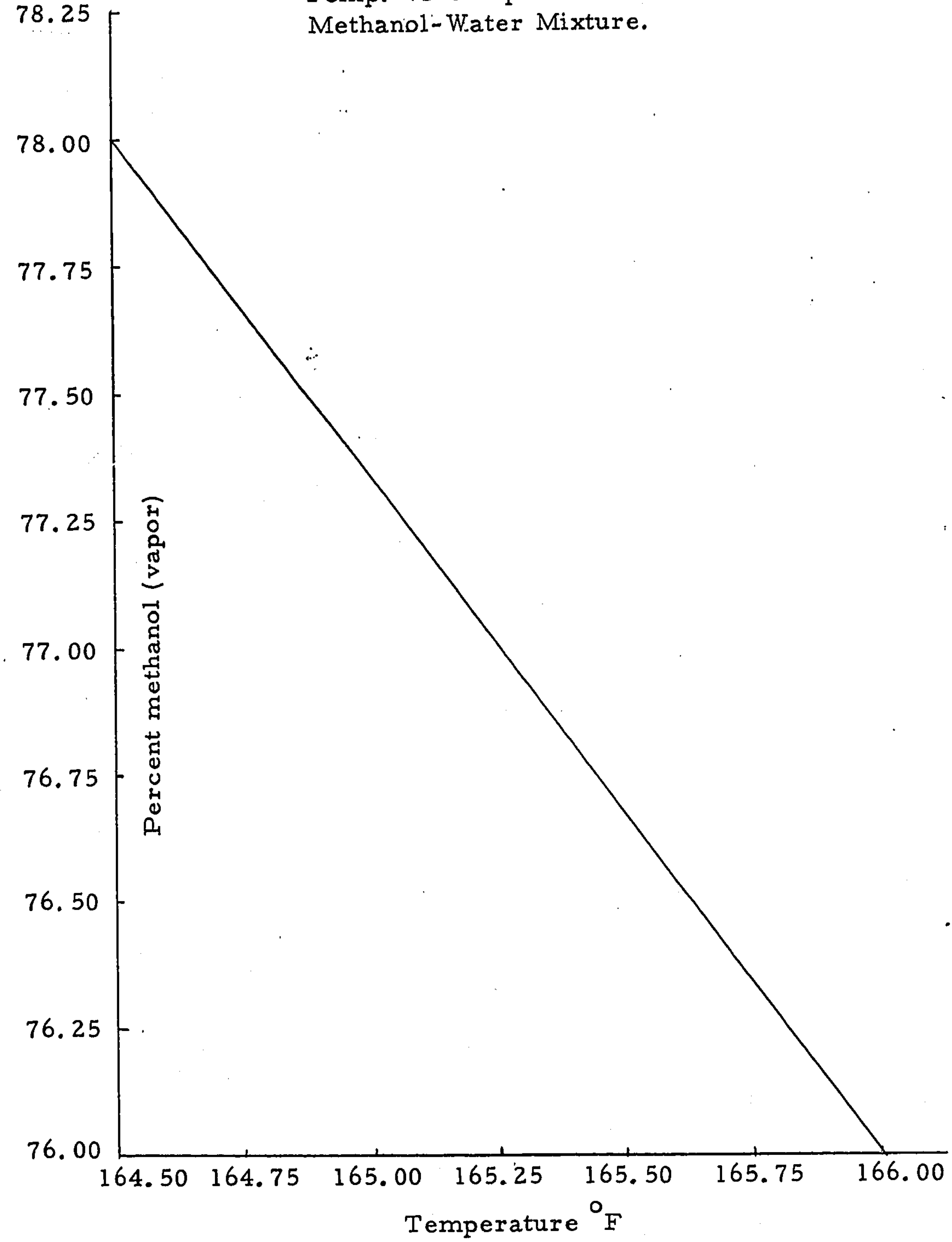


Fig. A.I.7

Temp. Vs Composition Curve for Methanol-Water Mixture.

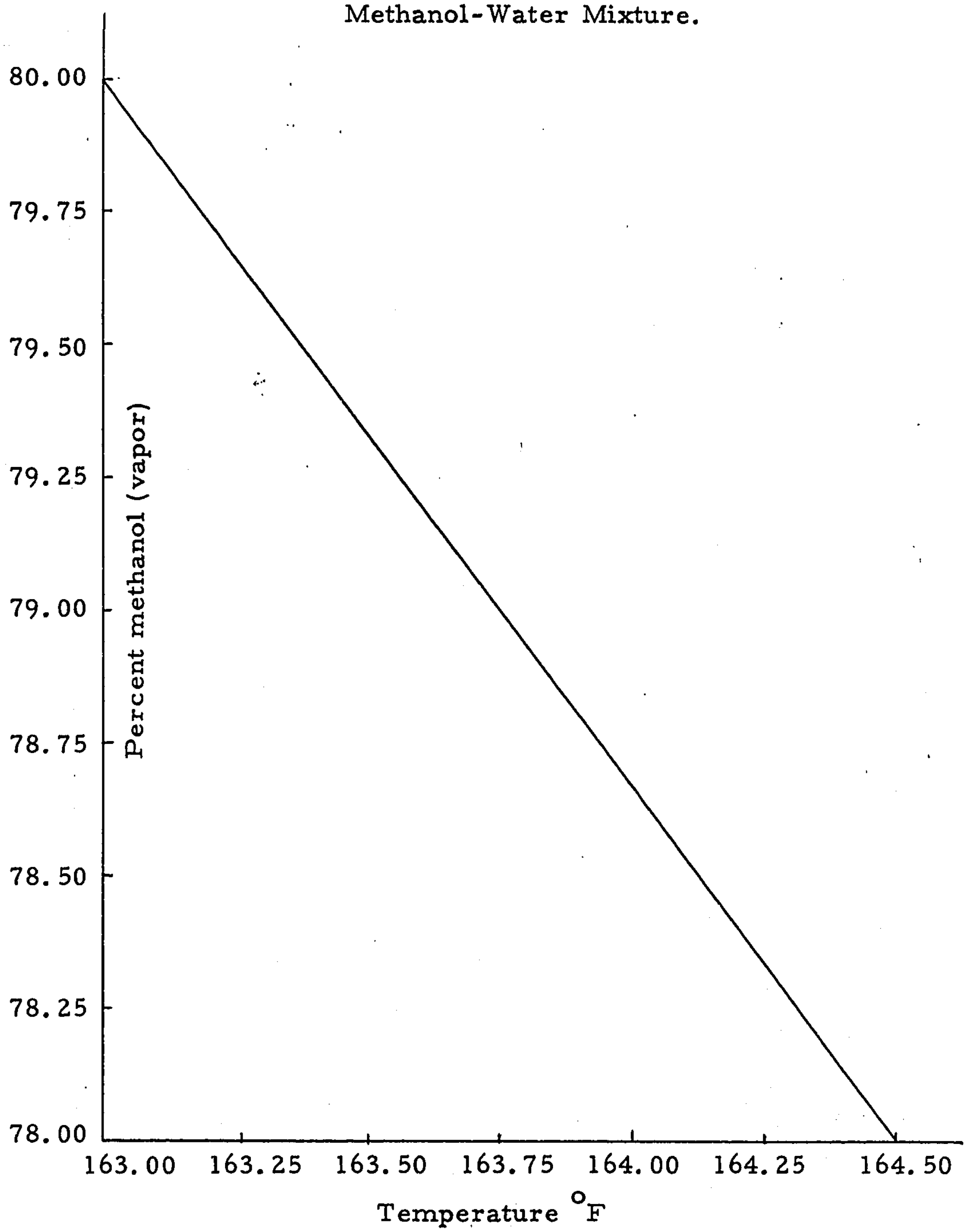
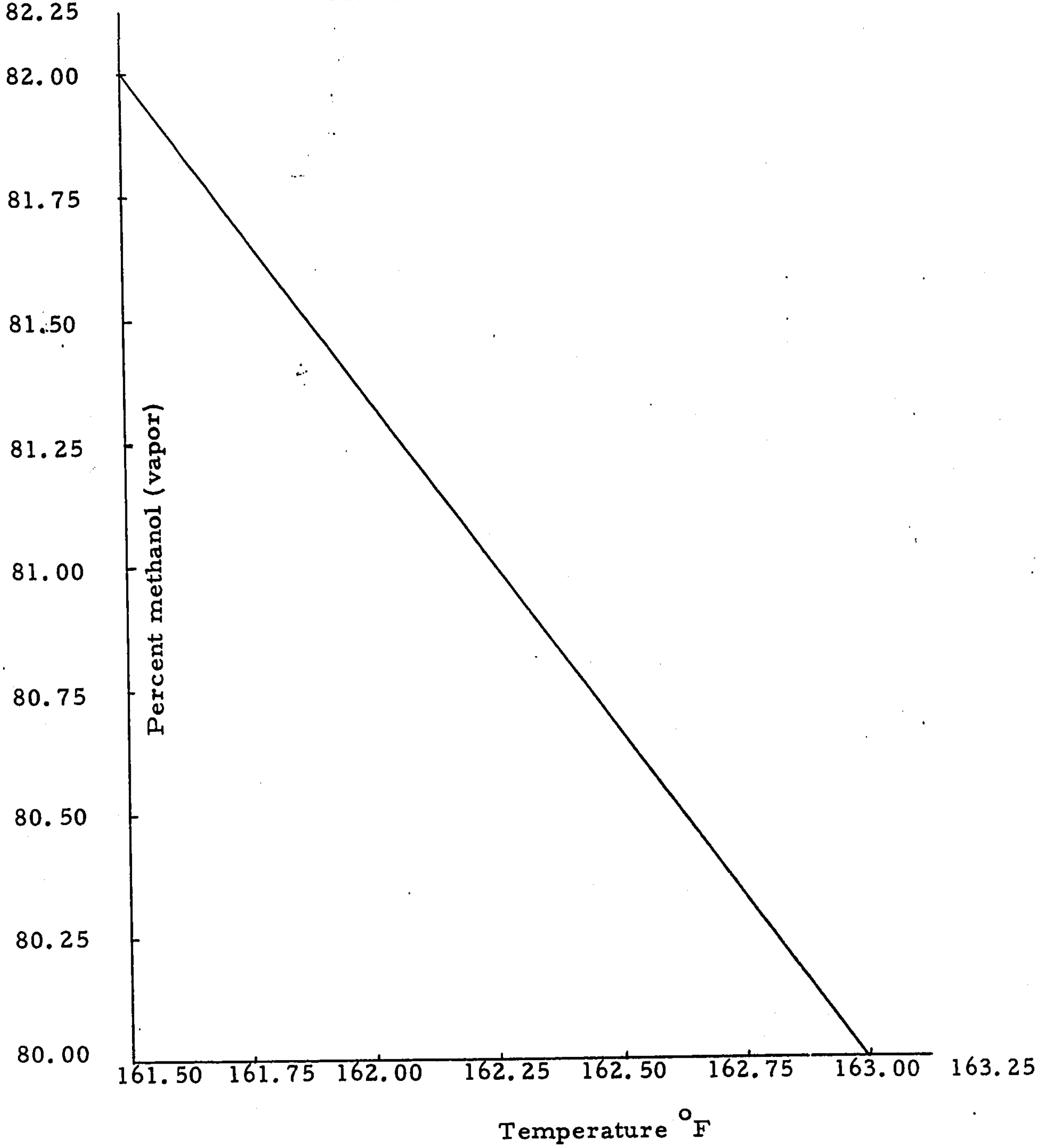


Fig. A.I.8

Temp. vs Composition Curve for
Methanol-Water Mixture.



APPENDIX II

Data for the Digital Computer Program

COMPOSITION TEST

7th Plate

Approximate shape of the curve:

$$f(t) = A\left[1-e^{-\frac{t_a}{-T}}\right]$$

where:

'A' is the magnitude of the change of composition due to 5. 5. percent step change in feed composition.

$t_a = t - t_1$

and t_1, T are time constants in minutes to be determined by least square error criterion.

Also $t_1 \simeq \frac{T}{10}$ $t_1 \simeq$ 0 - 2 minutes

DATA

Time (minutes)	Average absolute change in composition after 5. 5 percent step change in feed composition.
0	0.000
2	0.070
5	0.235
7	0.375
10	0.550
12	0.625
15	0.725
18	0.775
20	0.778
25	0.779
30	0.780
40	0.780
50	0.780

APPENDIX II

Data for the Digital Computer Program

COMPOSITION TEST

2nd Plate

Approximate shape of the curve:

$$f(t) = A_1 \left[1 - e^{-\frac{t_{a_1}}{T_1}} \right]$$

where:

A_1 is the magnitude of the change of composition due to 5 percent step change in feed composition.

$t_{a_1} = t - t_2$

and t_2, T_1 are time constants in minutes to be determined by least square error criterion.

Also $t_2 \simeq \frac{T_1}{10}$, $t_2 \simeq 0 - 2$ minutes

DATA

Time (minutes)	Average absolute change in composition after 5 percent step change in feed composition
0	0.000
2	0.032
5	0.275
7	0.455
10	0.700
12	0.850
15	1.000
18	1.075
20	1.125
25	1.165
30	1.200
40	1.225
50	1.250
60	1.270

APPENDIX II

Data for the Digital Computer Program

REFLUX TEST

7th Plate

Approximate shape of the curve:

$$f(t) = A_2 \left[1 - e^{-\frac{t_{a_2}}{T_2}} \right]$$

where:

'A_2' is the magnitude of the change of composition due to 10 percent step change in reflux.

$t_{a_2} = t - t_3$

amd t_3, T_2 are time constants in minutes to be determined by least square error criterion.

Also $t_3 \approx \frac{T_2}{10}$, $t_3 \simeq 0 - 2$ minutes

DATA

Time (minutes)	Average absolute change in composition after 10 percent step change in reflux
0	0.000
2	0.250
5	0.625
7	0.950
10	1.175
12	1.310
15	1.482
18	1.575
20	1.625
25	1.700
30	1.790
40	1.875
50	1.900
60	1.950
70	1.950

APPENDIX II

Data for the Digital Computer Program

REFLUX TEST

2nd Plate

Approximate shape of the curve:

$$f(t) = A_3 \left[1 - e^{-\frac{t_{a_3}}{T_3}} \right]$$

where:

'A_3' is the magnitude of the change of composition due to 10 percent change in reflux.

$$t_{a_3} = t - t_4$$

and t_4, T_3 are time constants in minutes to be determined by least square error criterion.

Also $t_4 \simeq \frac{T_3}{10}$, $t_4 \simeq 0$ - 2 minutes

DATA

Time (minutes)	Average absolute change in composition after 10 percent step change in reflux
0	0.000
2	0.002
5	0.033
7	0.039
10	0.052
12	0.058
15	0.064
18	0.071
20	0.078
25	0.083
30	0.083
40	0.088
50	0.096
60	0.098
70	0.102

APPENDIX II

Data for the Digital Computer Program

REBOIL TEST

7th Plate

Approximate shape of the curve:

$$f(t) = A_4 \left[1 - e^{-\frac{t_{a_4}}{T_4}} \right]$$

where:

'A_4' is the magnitude of the change of composition due to 10 percent step change in reboil.

$t_{a_4} = t - t_5$

t_5, T_4 are time constants in minutes to be determined by the least square error criterion.

Also $t_5 \simeq \frac{T_4}{10}$, $t_5 \simeq 0 - 2$ minutes

DATA

Time (minutes)	Average absolute change in composition after 10 percent change in reboil
0	0.000
2	0.450
5	1.500
7	1.825
10	2.125
12	2.275
15	2.350
18	2.430
20	2.475
25	2.500
30	2.510
40	2.515
50	2.550
60	2.575

APPENDIX II

Data for the Digital Computer Program

REBOIL TEST

2nd Plate

Approximate shape of the curve:

$$f(t) = A_5 \left[1 - e^{-\frac{t_{a_5}}{T_5}} \right]$$

where:

'A_5' is the magnitude of the change of the composition due to 10 percent change in reboil.

$t_{a_5} = t - t_6$

t_6, T_5 are time constants in minutes to be determined by least square error criterion.

Also $t_6 \simeq \frac{T_5}{10}$, $t_6 \simeq 0 - 2$ minutes

DATA

Time (minutes)	Average absolute change in composition after 10 percent change in reboil
0	0.000
2	0.250
5	0.750
7	0.925
10	1.075
12	1.125
15	1.200
18	1.250
20	1.275
25	1.277
30	1.278
40	1.300
50	1.320
60	1.325
70	1.325

APPENDIX III

ANALOG SIMULATIONS

Transfer Function of 7th Plate for the Change in Composition

Transmission delay:

Length of feed pipe = 12 feet

Discharge through the pipe = 400 gms/min.

X-section of the pipe = $\frac{9\pi}{64}$ sq. in.

Velocity of flow = $\frac{400}{(2.54)^3} \times \frac{64}{9\pi} = 4.6$ ft/min.

Time taken in transmission from feed tank to the feed plate = 2.6 minutes

This delay can be simulated as a simple first order lag.

Therefore, transfer function of transmission delay = $\frac{1}{1+2.6p}$

Propagation delay:

The propagation delay is approximated as 10 seconds from plate to plate.

Total propagation delay = .3 minutes

Transfer function of the propagation delay = $\frac{1}{1+.3p}$

The open-loop Transfer Function of the plate $= \frac{0.78}{5.5} \cdot \frac{1}{(1+0.7p)(1+1.85p)}$ where $\frac{0.78}{5.5}$ is the ratio of the change affected in the composition of 7th Plate to 5.5 percent step change in feed composition. Since the delays are non interacting, overall open-loop transfer function of 7th Plate

$$= \frac{1}{(1+2.6p)(1+.3p)(1+0.7p)(1+8.5p)} \cdot \frac{0.78}{5.5}$$

$$\simeq \frac{1}{(1+3.6p)(1+8.5p)} \times \frac{0.78}{5.5}$$

Transfer Function of 2nd Plate for the Change in Composition Test

Transmission delay in feed pipe = 2.6 minutes

Transfer function of transmission delay $= \frac{1}{1+2.6p}$

Propagation delay approximated as 10 seconds from plate to plate = 0.5 minutes

The open-loop transfer function of 2nd plate $= \frac{1.27}{5} \cdot \frac{1}{(1+0.85p)(1+11.1p)}$

where $\frac{1.27}{5}$ has usual meaning.

Since the delays are non interacting, overall transfer function for 2nd plate

$$= \frac{1}{(1+2.6p)(1+.5p)(1+0.85p)(1+11.1p)} \times \frac{1.27}{5}$$

$$\simeq \frac{1}{(1+3.95p)(1+11.1p)} \times \frac{1.27}{5}$$

Transfer Function of 7th Plate for the Change in Reflux

Transmission delay:

Length of reflux pipe = 4 feet

Cross sectional area of the pipe = $\frac{9\pi}{64}$ sq. in.

Discharge through the pipe = 100 gms/min.

Velocity of flow = $\frac{100}{(2.54)^3} \times \frac{64}{9\pi}$

= 1.15 ft/min.

Transmission delay in reflux pipe = 3.40 minutes

Transfer function of transmission delay = $\frac{1}{1+3.4p}$

Propagation delay:

Propagation delay approximated from plate to plate is 10 seconds.

Total propagation delay = .6 minutes

Transfer function of propagation delay = $\frac{1}{1+0.6p}$

The open-loop transfer function of 7th Plate = $\frac{1.95}{9.5} \times \frac{1}{(1+0.5p)(1+10.6p)}$

where $\frac{1.95}{9.5}$ has usual meaning.

Since the delays are non interacting, overall transfer function for 7th Plate

$$= \frac{1}{(1+3.4p)(1+0.6p)(1+0.5p)(1+10.6p)} \times \frac{1.95}{9.5}$$

$$\frac{1}{(1+4.5p)(1+10.6p)} \times \frac{1.95}{9.5}$$

Transfer function of 2nd plate for the change in Reflux

Transmission delay = 3.4 minutes

Transfer function of transmission delay = $\frac{1}{1+3.4p}$

Propagation delay = 1.2 minutes

Transfer function of the propagation delay = $\frac{1}{1+1.2p}$

The open-loop transfer function of the 2nd plate = $\frac{1}{(1+0.6p)(1+13.5p)} \times \frac{.102}{9.5}$

where $\frac{.102}{9.5}$ has usual meaning

The overall transfer function of the 2nd plate is:

$$= \frac{1}{(1+3.4p)(1+1.2p)(1+0.6p)(1+13.5p)} \times \frac{.102}{9.5}$$

$$\simeq \frac{1}{(1+5.2p)(1+13.5)} \times \frac{.102}{9.5}$$

Transfer function of the 7th plate for a change in Reboil

In this case, the transmission and propagations delays are negligible as compared to other delays.

The open-loop transfer function of 7th plate is:

$$= \frac{2.575}{1} \times \frac{1}{(1+.2p)(1+5.9p)}$$

where $\frac{2.575}{1}$ has usual meaning.

Transfer function of the 2nd plate for a change in Reboil

In this case the transmission and propagation delays are negligible as compared to other delays.

The open-loop transfer function of the 2nd plate

$$= \frac{1}{(1+.2p)(1+6.0p)} \times \frac{1.325}{1}$$

where $\frac{1.325}{1}$ is the ratio of the change of composition at 2nd plate to a change of 1 p.s.i. of steam in the reboiler.

Transfer function of Temperature Transmitter:

Since there is some delay involved in the detection through temperature transmitter, the transfer function can be written as $\frac{k_T}{1+S\tau_T}$ where 'k_T' is the gain of temperature transmitter. The delay 'τ_T' is of the order of fractions of a second and can be neglected as compared to other time constants. In that case a temperature transmitter can be represented by a simple gain device. The analog of the temperature transmitter is given in Fig. A.III.1.

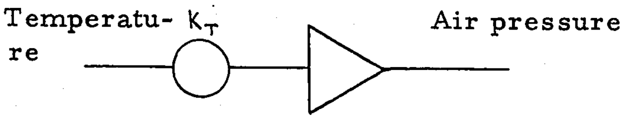


Fig. A.III.1. Analog of the Temperature Transmitter with Small Time Constant.

Transfer Function of the Controller:

The proportional plus integral controller used was pneumatic type and is sketched in Fig.A. III. 2.The functional representation of the above scheme is in Fig.A. III. 3.On solving the block diagram one gets the transfer function of the controller as:

$$Tc(t) = k_c \varepsilon \left[1 + \frac{1}{T_i} \int dt \right]$$

where:

Tc(t) is the transfer function of the controller.
k_c is the gain of the controller.
ε is the error in the forward loop.

The analog representation of the controller is given in Fig. A. III. 4.

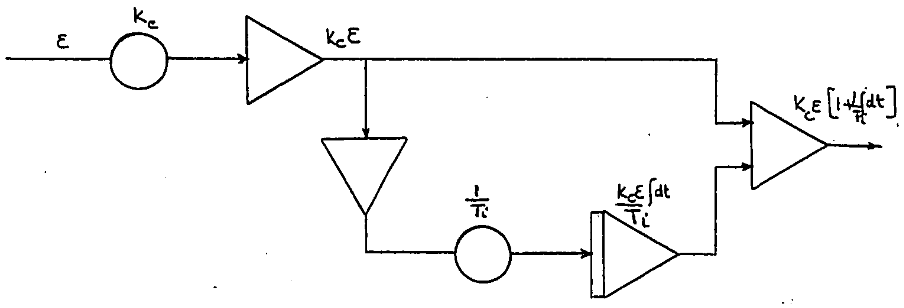


Fig. A. III. 4. Analog Representation of Integral plus Proportional Controller.

Transfer Functions of the Valves:

The characteristics of the valves are linear and since their time constants are negligible in comparision to the time constants of other components, they are represented as simple gain devices. The analog representation is shown in Fig. A. III. 5.

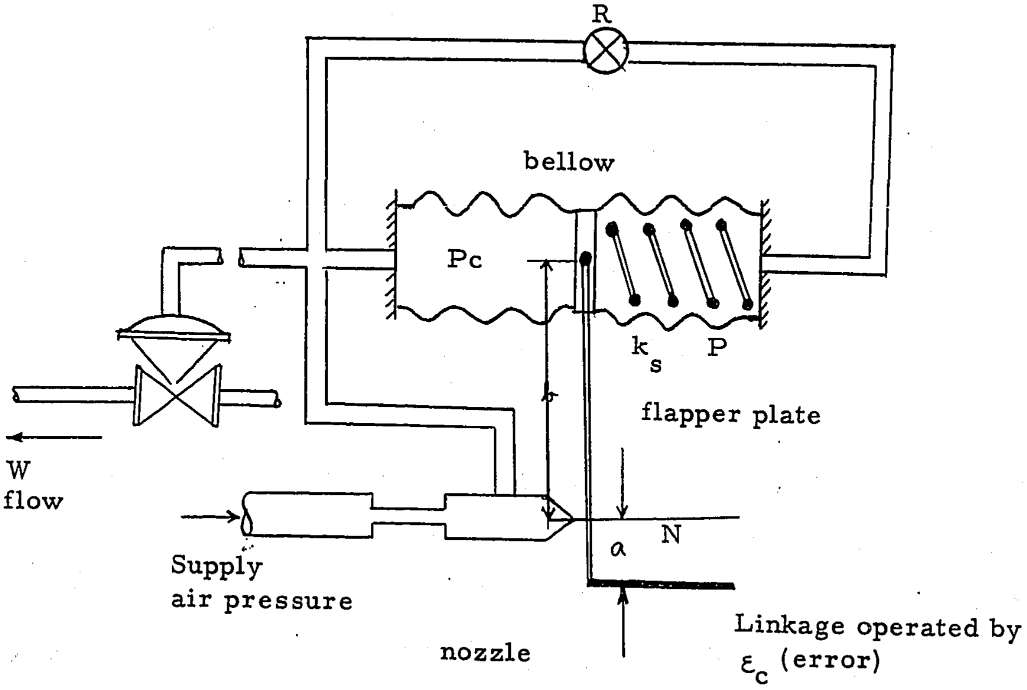


Fig. A.III.2. Schematic Diagram for a Pnenmatic Controller with Proportional and Integral Mode.

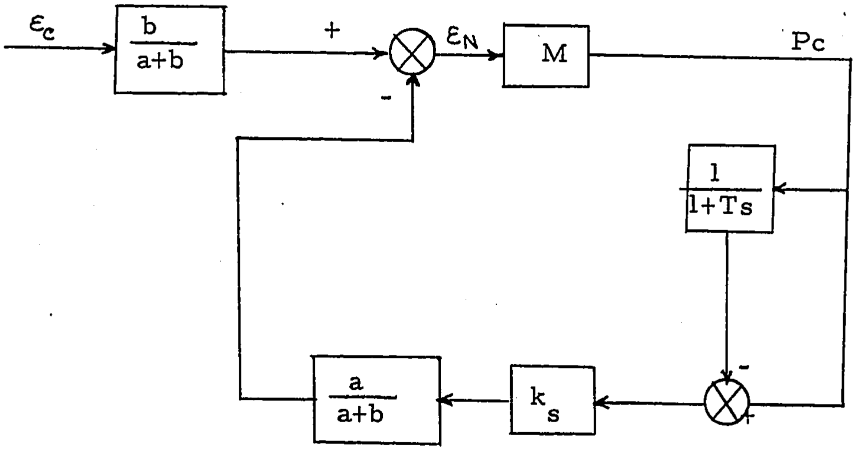


Fig. A.III.3. Block Diagram of the Pnenmatic Controller.

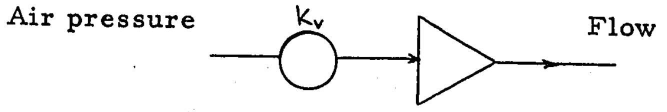


Fig. A.III.5. Analog Representation of a Linear Valve with Small Time Constant.

Analog Simulation of One Manipulated Variable Control Method:

The simulation of Fig. 5.1 and the table for potentiometer settings is given in Fig. A.III.6 and Table A.III.a.

Analog Simulation of Two Manipulated Variables Control Method:

The simulation of Fig. 5.4 and the table for potentiometer settings is given in Fig. A.III.7 and Table A.III.b.

TABLE A.III.a

Potentiometer Settings

Pot.	Coefficient	Coefficient	Scale	P.S.
00	k_T	$\frac{1}{1.38} \times \frac{12}{6}$	x $(\frac{1}{2})\ \frac{10^{-1}}{10^{-1}}$	0.725
01	k_c	0 ———	100	0.100-1.000
02	T_{i_7}	0 ———	100	various settings
03	k_{v_t}	$\frac{120}{6}$	x $\frac{10^{-1}}{1(10)}$	0.200
06	$\frac{k_{r_{7-1}}}{T_{r_{7-1}}}$	$\frac{1}{4.1} \times \frac{1.95}{9.5}$	x $\frac{10^{-1}}{10^{-1}}$	0.050
07	$\frac{1}{T_{r_{7-1}}}$	$\frac{1}{4.1}$	x $\frac{10^{-1}}{10^{-1}}$	0.244
08	$\frac{K_{r_{7-2}}}{T_{r_{7-2}}}$	.094	x $\frac{10^{-1}}{10^{-1}}$	.094
10	$\frac{1}{T_{r_{7-2}}}$	$\frac{1}{10.6}$	x $\frac{10^{-1}}{10^{-1}}$	.094
15	$\frac{K_{c_{7-1}}}{T_{c_{7-1}}}$	$\frac{1}{3.6} \times \frac{.76}{5.5}$	x $\frac{10^{-1}}{10^{-1}}$	.038
13	$\frac{1}{T_{c_{7-1}}}$	$\frac{1}{3.6}$	x $\frac{10^{-1}}{10^{-1}}$	.278

TABLE A. III. a (cont'd)

Pot.	Coefficient	Coefficient		Scale	P. S.
12	$\frac{K_{c_{7-2}}}{T_{c_{7-2}}}$	$\frac{1}{8.5}$	x	$\frac{10^{-1}}{10^{-1}}$	.118
11	$\frac{1}{T_{c_{7-2}}}$	$\frac{1}{8.5}$	x	$\frac{10^{-1}}{10^{-1}}$	.118
17	S. F.	4.03	x	$\frac{10^{-1}}{10^{-1}(10)}$	.403
21	S. F.	4.03	x	$\frac{10^{-1}}{10^{-1}(10)}$	.403
16	δx_f	$\frac{6}{10}$	x	$\frac{10^{-1}}{1}$	.06
30	S. P.	$\frac{78.1}{10}$	x	$\frac{10^{-1}}{1}$	.781

TABLE A.III.b.

Potentiometer Settings

Pot.	Coefficient	Coefficient	Scale	P.S.
00	K_{T_7}	$\frac{12}{6} \times \frac{1}{1.38}$	$\times \frac{1}{2} \times \frac{10^{-1}}{10^{-1}}$	0.725
01	K_{c_7}	0 ————————	100	0.100-1.000
02	T_{i_7}	0 ————————	100	. . .
03	k_{v_Y}	$\frac{120}{6}$	$\times \frac{10^{-1}}{1(10)}$	0.200
06	$\frac{K_{r_{7-1}}}{T_{r_{7-1}}}$	$\frac{1}{4.1} \times \frac{1.95}{9.5}\overset{\text{S.F.}}{(3.4)}$	$\times \frac{10^{-1}}{10^{-1}}$	0.170
07	$\frac{1}{T_{r_{7-1}}}$	$\frac{1}{4.1}$	$\times \frac{10^{-1}}{10^{-1}}$	0.244
08	$\frac{K_{r_{7-2}}}{T_{r_{7-2}}}$	$\frac{1}{10.6}$	$\times \frac{10^{-1}}{10^{-1}}$	.094
09	$\frac{1}{T_{r_{7-2}}}$	$\frac{1}{10.6}$	$\times \frac{10^{-1}}{10^{-1}}$	.094
11	$\frac{K_{s_{7-1}}}{T_{s_{7-1}}}$	$\frac{1}{.2}$	$\times \frac{10^{-1}}{10^{-1}(10)}$	.500
12	$\frac{1}{T_{s_{7-1}}}$	$\frac{1}{.2}$	$\times \frac{10^{-1}}{10^{-1}(10)}$	.500

TABLE A.III.b. (cont'd)

Pot.	Coefficient	Coefficient		Scale	P.S.
19	$\frac{K_{s_{7-2}}}{T_{s_{7-2}}}$	$\frac{1}{5.9} \times \frac{.257}{1}$	x	$\frac{10^{-1}}{10^{-1}}$	.169
34	$\frac{1}{T_{s_{7-2}}}$	$\frac{1}{5.9}$	x	$\frac{10^{-1}}{10^{-1}}$	.169
33	S.F.	3.4	x	$\frac{10^{-1}}{10^{-1}(10)}$	.34
17	k_{T_2}	$\frac{12}{6} \times \frac{1}{1.38}$	x	$\frac{10^{-1}}{2\times10^{-1}}$	.725
18	k_{c_2}	0		100	.0100-1.00
20	T_{i_2}	0		100	Do
21	k_{v_s}	$\frac{12}{6}$	x	$\frac{1}{1(10)}$	.200
22	$\frac{k_{s_{2-1}}}{T_{s_{2-1}}}$	$\frac{1}{.2}$	x	$\frac{10^{-1}}{1}$	.500
23	$\frac{1}{T_{s_{2-1}}}$	$\frac{1}{.2}$	x	$\frac{10^{-1}}{1}$	.500
5	$\frac{k_{s_{2-2}}}{T_{s_{2-2}}}$	$\frac{1}{6} \times \frac{.1320}{1}$	x	$\frac{10^{-1}}{10^{-1}}$	.022
8	$\frac{1}{T_{s_{2-2}}}$	$\frac{1}{6}$	x	$\frac{10^{-1}}{10^{-1}}$	.167
36	S.F.	6.7	x	$\frac{10^{-1}}{10^{-1}(10)}$	.67

TABLE A.III.b. (cont'd)

Pot.	Coefficient	Coefficient	Scale	P.S.
25	$\frac{k_{c_{7-1}}}{T_{c_{7-1}}}$	$\frac{1}{3.6} \times \overset{S.F.}{\frac{.76\,(34)}{5.5}} \times$	$\frac{10^{-1}}{10^{-1}}$	.13
27	$\frac{1}{T_{c_{7-1}}}$	$\frac{1}{3.6} \times$	$\frac{10^{-1}}{10^{-1}}$	.278
13	$\frac{k_{c_{7-2}}}{T_{c_{7-2}}}$	$\frac{1}{8.5} \times$	$\frac{10^{-1}}{10^{-1}}$	.118
15	$\frac{1}{T_{c_{7-2}}}$	$\frac{1}{8.5} \times$	$\frac{10^{-1}}{10^{-1}}$	.118
28	$\frac{k_{c_{2-1}}}{T_{c_{2-1}}}$	$\frac{1}{3.75} \times \overset{S.F.}{\frac{1.27(67)}{5}} \times$	$\frac{10^{-1}}{10^{-1}}$	.267
32	$\frac{1}{T_{c_{2-1}}}$	$\frac{1}{3.75} \times$	$\frac{10^{-1}}{10^{-1}}$	.267
39	$\frac{k_{c_{2-2}}}{T_{c_{2-2}}}$	$\frac{1}{11.1} \times$	$\frac{10^{-1}}{10^{-1}}$	.091
24	$\frac{1}{T_{c_{2-2}}}$	$\frac{1}{11.1} \times$	$\frac{10^{-1}}{10^{-1}}$	.091
30	S.P.	$\frac{78.1}{10} \times$	$\frac{10^{-1}}{10^{-1}}$	.781
16	S.P.	$\frac{52.9}{10} \times$	$\frac{10^{-1}}{1}$	.529
25	$\delta x_f'$	$\frac{6}{10} \times$	10^{-1}	.06

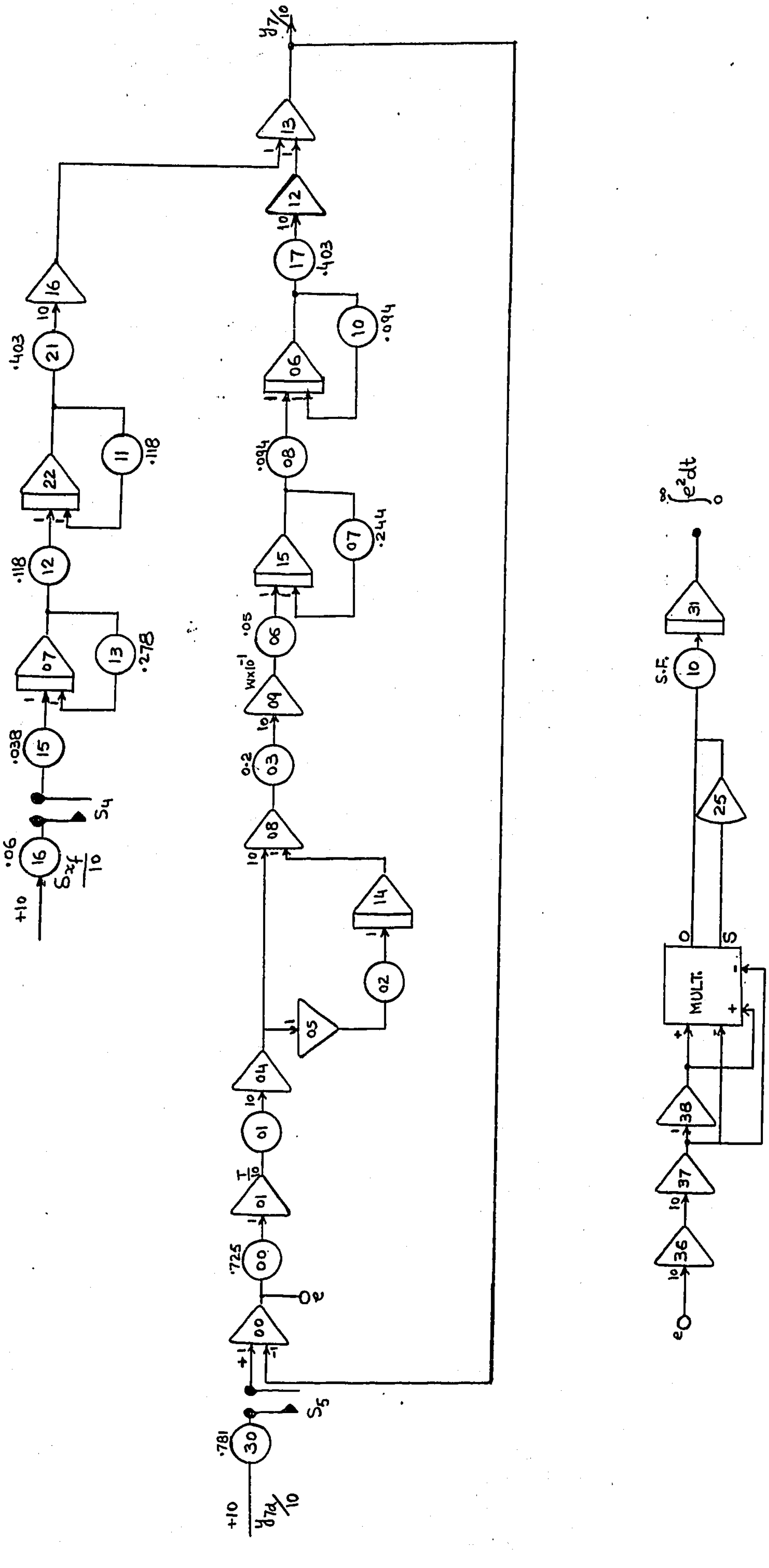


Fig. A. III. 6. Analog Simulation of the M. V. Control Method.

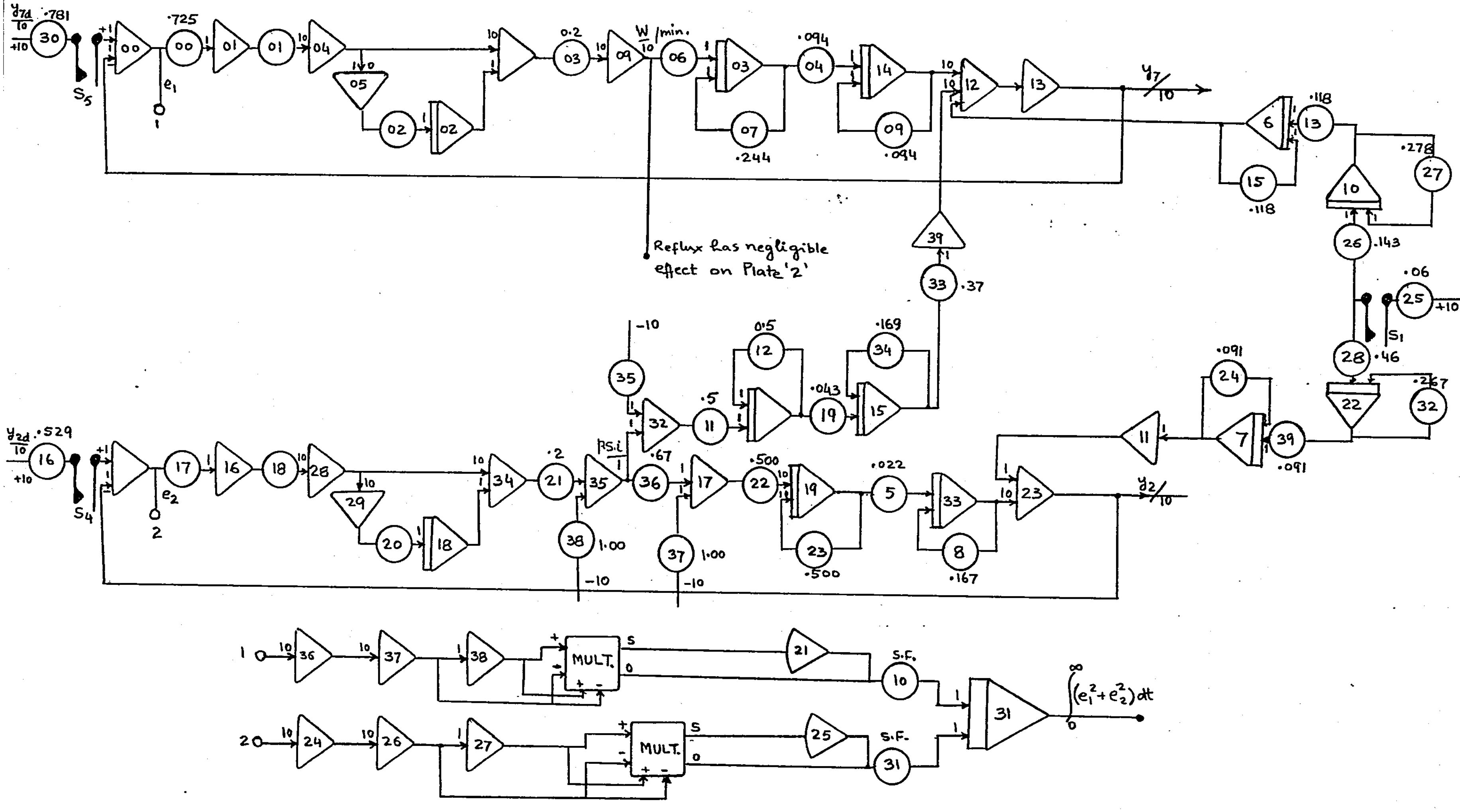


Fig. A.III.7. Analog Simulation of Two M.V. Control Method.

The blocks in Figs. 5.1, 5.7 are defined as below:

k_{T_7}	Gain of the temperature transmitter in the control loop for 7th Plate.
k_{T_2}	Gain of the temperature transmitter in the control loop for 2nd Plate.
k_{v_r}	Gain of the reflux valve.
k_{v_s}	Gain of the steam valve.
k_{c_7}	Gain of the controller in the control loop for 7th Plate.
T_{i_7}	Time constant of integration of the controller in the 7th plate loop.
k_{c_2}	Gain of the controller in the control loop for 2nd Plate.
T_{i_2}	Time constant of integration of the controller in the 2nd plate loop.
y_7	Output composition of 7th Plate.
y_{7_d}	Desired output composition of 7th Plate.
y_{7_c}	Response of the 7th Plate to a step change in feed composition.
y_{7_r}	Response of 7th Plate to a step change in reflux.
y_{7_s}	Response of 7th Plate to a step change in reboil.
y_{2_c}	Response of 2nd Plate to a step change in feed composition.
y_{2_r}	Response of 2nd Plate to a step change in reboil.
y_2	Output composition of 2nd Plate.
y_{2_d}	Desired output composition of 2nd Plate.
δx_f	Small change in the feed composition.

REFERENCES

1. E. Mishkin and L. Braun. "Adaptive control systems" 1961 Chapters 3 & 9, McGraw-Hill Book Co. N. Y.
2. D. P. Eckman (Editor). "Systems: Research and Design". Proceedings of the first systems symposium at Case Institute of Technology. John Wiley & Sons Inc. N. Y.
3. D. Graham and R. C. Lathrope. The Synthesis of "Optimum" Transient Response: Criteria & Standard Forms. Trans. AIEE, Vol., 72, pt. 2, pp. 278-288; November, 1953.
4. A. C. Hall. "The analysis and synthesis of linear servomechanisms". The Technology Press, M.I.T., Cambridge, p. 19; 1943.
5. R. C. Oldenbourg and H. Sartotious. "The Dynamics of Automatic Control" book published by ASME, p. 66; 1948.
6. C. Mack. "Calculations of the Optimum Parameters for a following System". Phil. Mag., Vol. 40, pp. 922-928, Sept. 1949.
7. T. M. Stout. "A note on control area". J. Appl. Phys. Vol. 21, pp. 1129-1131; November, 1950.
8. J. Lanning and R. H. Battin. "Random Processes in Automatic Control". McGraw-Hill Book Co., Inc., N. Y. 1956.
9. P. T. Nims. "Some design criteria for automatic control". Trans. AIEE, Vol., 70, pt. 1, pp. 606-611, 1951.
10. R. R. Caldwell and V. C. Rideout. "A differential analyzer study of certain nonlinearity damped servomechanism". Trans. AIEE, Vol., 72, pt. 2, pp. 165-169, July 1953.
11. F. C. Fickeisen and T. M. Stout. "Analog method for optimum servomechanism design". Trans. AIEE, Vol. 71, pt. 2, pp. 244-250, Nov. 1952.

12. G. W. Anderson, J. A. Aseltine, A. R. Marcini and C. W. Sarture. "A self adjusting system for optimum dynamic performance". 1950 IRE National Convention Record, pp. 4, pp. 182-190.

13. N. Wiener. "The extrapolation, interpolation and smoothing of stationary time series". John Wiley & Sons Inc., N. Y. 1948.

14. J. H. Milsum. "Adaptive Control of Processes by an Economic Criterion". Proceedings of 1st IFAC Conference, Vol. 4, pp. 231-240, 1960.

15. A. A. Feldbaum. "Automatic Optimalizer". Automatika Telemekanika (English). Vol. 19, pp. 710-728, 1958.

16. A. A. Feldbaum. "Problems in Statistical Theory of Systems of Automatic Optimization". Proceedings of 1st IFAC Conference, Vol. 2, pp. 547-555, 1960.

17. H. H. Rosenbrock. "Distinctive Problems of Process Control". Chemical Engineering Progress Vol. 58, No. 9, September 1962.

18. Seymour Calvert and George Coulman. "Feed Forward Control", "Its Future in Chemical Plants". CEP. Vol. 57, No. 9, Sept. 1961.

19. D. M. Boyd. Petrol Refinery, 1948, 27, 533, Idem, ibid, 595.

20. V. V. Tivy. Petrol Refinery, 1948, 27, 603.

21. W. R. Marshall and R. L. Pigford. "The applications of differential equations to chemical engineering". 1947, 1. 144, (University of Delware).

22. W. L. Wilkinson and W. D. Armstrong. "Transient Response of a Distillation Column". Plant and Process Dynamic Characteristics. 1957, pp. 56-71. (Butterworth Scientific Publications, London).

23. H. Voetter. "Response of concentration in a Distillation Column". Plant & Process Dynamics Characteristics. 1957, pp. 73-100. (Butterworth Scientific Publications, London).

24. O.P. Campbell. "Process Dynamics". 1958, p. 225, John Wiley & Sons Inc. N.Y.

25. A. Acrivos and N.R. Amundson. "Solution of Transient Stagewise Operations on an Analog Computer". Industrial Engg. Chemistry 1953, Vol. 45, p. 467.

26. A. Rose and T.J. Williams. "Automatic Control in Continuous Distillation". Industrial Engg. Chemistry, 1955, Vol. 47, p. 2284.

27. T.J. Williams, R.T. Harnett and A. Rose. "Automatic Control in Continuous Distillation". Industrial Engg. Chemistry, 1956, Vol. 48, p. 1008.

28. A. Rose, C.L. Johnson and T.J. Williams. "Transient and Equilibration Time in Continuous Distillation". Industrial Engg. Chemistry, 1956, Vol. 48, p. 1173.

29. T.J. Williams and R.T. Harnett. "Automatic Control in Continuous Distillation". Chemical Engineering Progress. 1957, Vol. 53, p. 220.

30. T.J. Williams. "Instrumentation and Control of Distillation Columns". Industrial Engg. Chemistry. 1950, Vol. 50, p. 1214.

31. J.E. Rinjsdrop and A. Maarleveld. "Proceedings of the Joint Symposium on Instrumentation and Computation", 1959, p. 135. (London: The Institute of Chemical Engineers).

32. O. Rademaker and J.E. Rinjsdorp. "Proceedings of the Fifth World Petroleum Congress". 1959, Section VII, p. 59. (New York: The American Petroleum Institute).

33. D. E. Lamb and R. L. Pigford. "Dynamic characteristics and Analog Simulations of Distillation Columns". Paper presented to A.I.Ch.E., Annual Meeting, San Francisco, December, 1959.

34. M.F. Baber, L.L. Edwards, W.T. Harper, M.D. Witte and J.A. Gerster. "Experimental Transient Response of a Pilot Plant Distillation Column". Paper presented to A.I.Ch.E. Annual Meeting, Washington, December, 1960.

35. J.P. Bromley. "Analog Studies of Process Control Systems". Proceedings of the International Seminar of Analog Computations Applied to the Study of Chemical Process, Bruxelles, 21-23 November, 1960.

36. A. Rose and R.C. Johnson. "The Theory of Unsteady State Batch Distillation Curves". CEP, 1953, Vol. 49, p. 15.

37. A. Rose, R.C. Johnson and T.J. Williams. "Stepwise plate to plate computation of Batch Distillation curves". Industrial Engg. Chemistry, 1951, Vol. 43, p. 2459.

38. H.H. Rosenbrock. "An Investigation of the Transient Response of Distillation Columns, Part I Solution of Equations". Trans. I. Ch.E., 1957, Vol. 35, p. 347.

39. H.H. Rosenbrock, A.B. Tavendale, C. Storey and J.A. Challis. Proceedings of IFAC Conference 1960, Vol. 4, p. 303. (London: Butterworth Scientific Publications).

40. J. Endtz, J.M.L. Janssen and J.C. Vermeulen. "Measuring Dynamic Responses of Plant Units". Plant & Process Dynamic Characteristics. 1957, 1. 170. (London: Butterworth Scientific Publications).

41. W.R. Armstrong and W.L. Wilkinson. "An Investigation of the Transient Response of a Distillation Column. Part II; Experimental Work and Comparison with Theory". Trans, I.Ch.E. 1957, Vol. 35, p. 352.

42. H.H. Rosenbrock. "The Control of Distillation Columns". Trans. I.Ch.E., Vol. 40, 1962.

BIBLIOGRAPHY

In addition to the references listed on pages 125 - 129, the following items are relevant.

1. J. G. Truxal. "Automatic Feedback Control System Synthesis". McGraw-Hill Book Co. Inc. 1955.
2. R. L. Ackoff. "Scientific Method: Optimization Applied Research Decision". 1962, John Wiley & Sons Inc. N. Y.
3. J. H. Milsum. "Economic Performance Criteria for Optimizing Control Systems". Trans. E.I.C. Vol. 5 & 3, 1961, pp. 148-154.
4. J. H. Milsum. "Hill Climbing and Computer Control". Summer Seminar of Associate Committee of Automatic Control (N.R.C.), on Modern Automatic Control Theory, at McGill University, 1962.
5. J. R. Dickinson. "A computer program for system optimization". Trans. E.I.C. Vol. 2, No. 4, Dec. 1958.
6. W. C. Shultz and V. C. Rideout. "Control System Performance Measures: Past, Present and Future". I.R.E. Transactions on Automatic Control, pp. 22-35, February, 1961.
7. H. S. Tsien. "Engineering Cybernetics". 1954, McGraw-Hill Book Co. N. Y.
8. C. S. Herzfeld. "Temperature, its measurement and control in science and industry". Part 2. Reinhold Publishing Corporation Chapman & Hall Ltd., London.
9. J. C. Chu, S. L. Wang, S. L. Levy and R. Paul. "Vapor-Liquid Equilibrium Data". 1956. J. W. Edwards Publisher Inc., Ann Arbor, Michigan.

10. P.L. Waher. "Distillation". 1963. Engineering Extension Service. Texas A. and M. College Systems.

11. W.H. Walker, W.K. Lewis, W.H. McAdams and E.R. Gilliland. "Principles of Chemical Engineering". McGraw-Hill Book Co., 1937.

12. R.E. Treybal. "Mass Transfer Operations". McGraw-Hill Book Co., 1955.

13. C.S. Robinson and E.R. Gilliland. "Elements of Fractional Distillation". McGraw-Hill, New York.

VITA

Name: M. Noman Jafri

Born: Pakistan, September, 7th, 1939.

Educated:

Primary: Islamia High School, Lahore.

Secondary: Islamia College, Lahore.

University: Government College of Engineering and Technology, University of the Panjab, Lahore, West Pakistan.

Courses: Electrical Engineering.

Degree: B.Sc. (Hons). Engineering, 1960.