"MODELING AND CONTROL OF BINARY DISTILLATION COLUMN USING LabVIEW"

A DISSERTATION SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF

MASTER OF ENGINEERING
(CONTROL & INSTRUMENTATION)

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CERTIFICATE

This is to certify that the work presented in this project entitled **"Modeling and Control of Binary Distillation Column Using LabVIEW"**, in partial fulfilment of the requirement for the award of the degree of Master of Engineering in Control & Instrumentation submitted by Puneet Mishra (08/C&I/09) to the Department of Electrical Engineering, is a record of the student's work carried out under my supervision and guidance.

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ABSTRACT

Distillation is a continuous process in the petroleum and the chemical industries. A high amount of energy used in the chemical and petrochemical industries is consumed in the distillation process, since large amount of heat transfer takes place between the trays of distillation column. Thus, there is a need of energy efficient process to be designed and controlled, in order to make the final and the intermediate products of the distillation process of desired quality and the whole process being more economic.

In the present study, graphical programming of LabVIEW software has been utilized to develop model for distillation column and also to control the product stream composition. Use of virtual instrumentation for the modeling of systems and controlling the process variables improves the performance and reliability of the whole plant. Virtual instrumentation saves the extra cost, time and energy that are incurred while setting up traditional instrumentation systems. It is a latest form of modern measurement/monitoring technology where all types of measurements are done on front panels created on PC screen. This work explores the very capability of Virtual instrumentation to monitor and control the process variables, which is composition of the product stream of the distillation process, and the use of LabVIEW in the field of Process control.

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CHAPTER I

INTRODUCTION

1.1 INTRODUCTION: Distillation is a continuous process in the petroleum and the chemical industries. Nearly, 60% of the energy used in the chemical and petrochemical industries is consumed in the distillation process, since large amount of heat transfer takes place between the trays of distillation column. Thus, there is a need of energy efficient process to be designed and controlled, in order to make the final and the intermediate products of the distillation process of desired quality and the whole process being more economic.

A Distillation column contains non - linearities, and composition interactions between the stages due to the counter flow of vapour and liquid [1]. Various control strategies have been designed and are being used for controlling the distillation process to maintain the composition of top and the intermediate products. In this thesis, modeling of distillation column has developed and, a PID control scheme has been adapted to get the end products of required quality.

1.2 PARAMETERS AND VARIABLES OF DISTILLATION COLUMN: Distillation is the process used for separating the different components from a liquid feed stream and purifies them. The apparatus used for this purpose is called “Distillation Column”[14]. The distillation column consists of many trays, condenser, reboiler, and a vertical column for the separation purpose. To achieve the purest form of a component i.e. to achieve the desired composition of a product, one has to control various variables of the distillation column such as temperature of trays , reflux flow rate, distillate flow rate, vapour boilup rate and sometimes the pressure in the column also. These variables can be altered by building a control law based on the model of the distillation column.

This model of distillation column can be build using the differentials equations which describes the relationship between the various variables of the column. Some of these variables act as disturbances, some as manipulated variables, some as controlled variables and some as

uncontrolled variables. Modeling of a distillation column contains all of these variables related with each other in a special manner which obeys the laws of basic thermodynamics and mass – energy balance equations.[9]

Various variables related to the distillation column can be categorized in different categories defined above, as, [9]

1. **Disturbance:** This type of variables produce change in the output of a model and some kind of control strategies are employed to nullify the effect of the disturbances. In a distillation column disturbances are,
   - **a.** Feed Flow Rate
   - **b.** Feed Composition.

2. **Manipulated Variables:** These variables act as input to the plant which are varied in such a manner, i.e. according to the control law, to maintain the output of the model at setpoint. In a distillation column manipulated variables can be,
   - **a.** Reflux Flow Rate
   - **b.** Reboiler Heat
   - **c.** Distillate Flow Rate
   - **d.** Bottom Flow Rate
   - **e.** Cooling Flow Rate

3. **Controlled Variables:** Controlled variables are the output of the model or plant which has to be maintained at the set point by varying the manipulated variables irrespective of the effect of the disturbances. In a distillation process controlled variables are,
   - **a.** Distillate Composition
   - **b.** Bottom Composition
   - **c.** Level of the Reflux Drum
   - **d.** Level of the Column Base
   - **e.** Pressure of the Column

4. **Uncontrolled Variables:** Uncontrolled variables are those variables which are just used in the modeling equations and can't be controlled by any means used in the modeling. In the model used in this dissertation, temperatures of various trays act as uncontrolled variables.

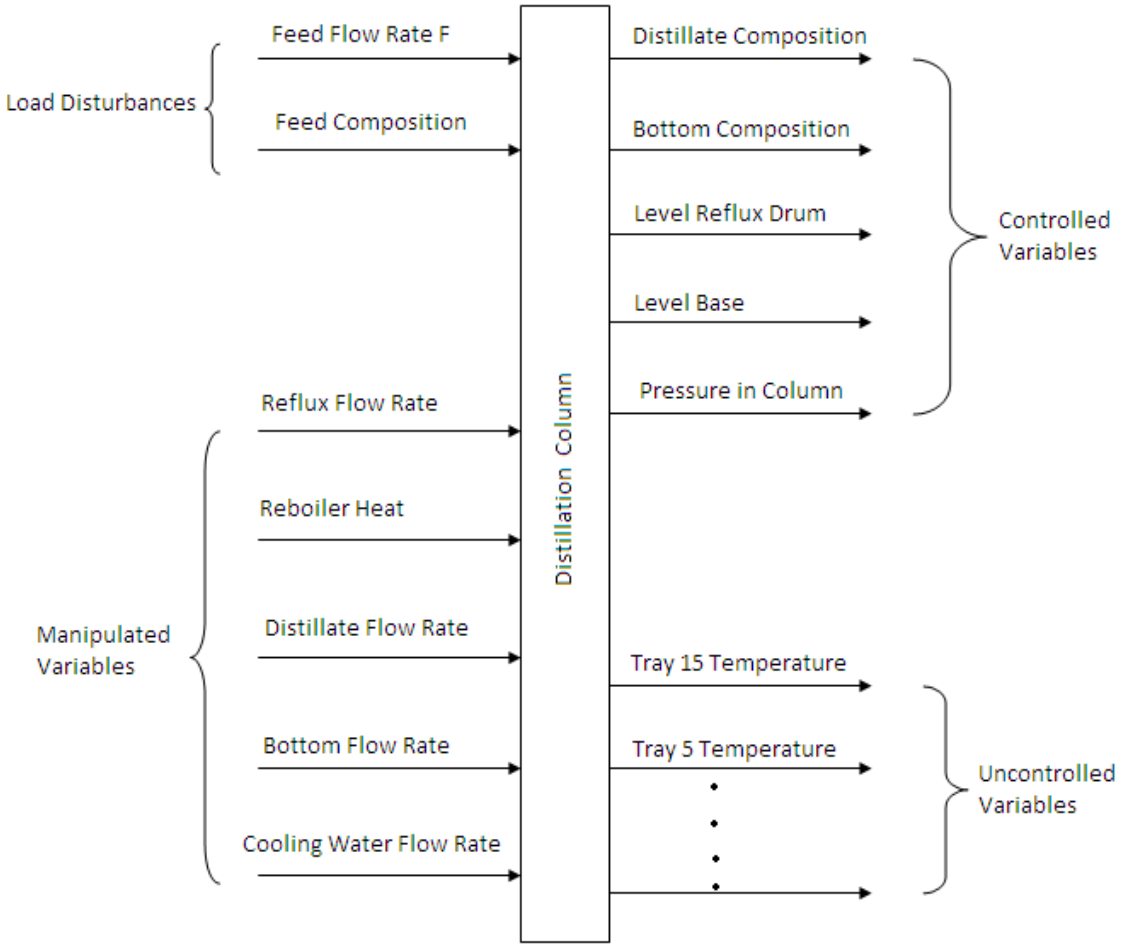

Fig. 1.1 Different Variable in Distillation Column

Thus a model is developed based on the relations between the various variables which obey the laws of Thermodynamics, Mass - Energy Transfer etc.

1.3 METHODOLOGY:

In the present study, LabVIEW software, a virtual instrumentation facility has been explored to develop a model of Distillation Column and also to control the various variables such as composition of the different products (like composition of Methanol and Water in a distillation

process to separate methanol and water). Use of virtual instrumentation for the measurement and monitoring the composition of products of the distillation process improves the performance and reliability of the system. The controller for controlling the final composition of the process is also designed using LabVIEW.

1.3.1 Why LabVIEW: Conventional methods of controlling uses hardwared controllers for the controlling purposes of signal such as op-amp, resistors etc. to make controllers which makes the work of the control engineer cumbersome as the system engineer has to develop and then to design the same through different components either electrical or pneumatic. This has limited reliability. LabVIEW provides an alternative solution to enhance the reliability and flexibility. It uses a graphical programming language, in which the system engineer exploits the available icons in LabVIEW Library to develop the new techniques and the strategies of controlling. Thus, it saves extra cost, time and energy that are incurred while setting up traditional instrumentation system. It is an innovative form of measurement/monitoring technology where all types of measurements are done on front panels created on PC screen. Moreover, the end user i.e. the plant operator has various options and he can monitor the physical variables remotely on the computer screen i.e. on the front panel of the LabVIEW.

In real situations data can be collected with the help of data acquisition technique and given to PC through specific interfacing device. Then this raw data can be processed or analyzed by using VI software, LabVIEW. The VI software is powerful, and can acquire, analyze and present any signal efficiently and hence this can be very helpful for devising methods to avoid their harmful effects.

1.4 OBJECTIVE OF THIS DISSERTATION: The objectives of this dissertation are,

1. First objective of this dissertation is to develop a model for the Binary Distillation Column relating different variables such as composition of the Bottom Products and Distillate product. This model contains Feed Composition (Z_f) and the feed flow (F_f) as the input Disturbances and Distillate Flow rate and Bottom flow rate as the manipulated variables i.e. output of the controller.

2. Second objective of the dissertation is to develop a control strategy to maintain the product of the distillation at the fixed composition level i.e. at set point. This dissertation also explores the effect of the various controller parameter values on the response of the distillation column model.

1.5 DISSECTION OF THE DISSERTATION:

The material of this dissertation has been organized in seven chapters. The contents of the chapters are briefly outlined as indicated below.

Chapter-1 discusses on the need of controlling the distillation column and a brief outline about the process and the involved parameters in the distillation process and gives a brief objective of this thesis.
Chapter-2 discusses on Literature Review.
Chapter-3 discusses about the virtual instrumentation and presents features and effectiveness of LabVIEW.
Chapter-4 gives a detailed explanation about the distillation process and its different types and aspects.
Chapter-5 discusses about the mathematical modeling and the control strategy employed in the thesis.
Chapter-6 discusses the integration of the distillation column model with LabVIEW.
Chapter-7 presents the results and the scope for further study.

1.6 CONCLUSION:

This chapter gives brief introduction about distillation column modeling and control, brief idea about disturbances and other variables included in the distillation column control and discusses about the application of Virtual instrumentation for distillation column. Also objective of this thesis and brief outline of the project design is presented.

CHAPTER II

LITERATURE REVIEW

2.1 DEVELOPMENTAL HISTORY OF LabVIEW: In recent years, the rapid development of micro-electronics technology, computer technology, network communication technology and software technology promote the rapid development of virtual machines technology. In labVIEW environment, real time power quality monitoring can be developed using Virtual Instrumentation concept. This is done with data acquisition system, which can transmit the measured signal any far-away place via guided or unguided media without distorting the original signals.

Virtual Instrumentation is an interdisciplinary field that merges sensing, hardware, and software technologies in order to create flexible and sophisticated instruments for control and monitoring applications. The concept of virtual instrumentation was born in late 1970s, when microprocessor technology enabled a machine's function to be more easily changed by changing its software. The flexibility is possible as the capabilities of a virtual instrument depend very little on dedicated hardware. A history of virtual instrumentation is characterized by continuous increase of flexibility and scalability of measurement equipment. Nearly all of the instrument control programs were written in BASIC, because it had been the dominant language used with dedicated instrument controllers. It required engineers and other users to become programmers before becoming instrument users, so it was hard for them to exploit potential that computerized instrumentation could bring. Therefore, an important milestone in the history of virtual instrumentation happened in 1986, when National Instruments introduced LabVIEW 1.0 on a PC platform. LabVIEW introduced graphical user interfaces and visual programming into computerized instrumentation, joining simplicity of a user interface operation with increased capabilities of computers. Today, the PC is the platform on which most measurements are made, and the graphical user interface has made measurements user-friendlier. As a result, virtual instrumentation made possible decrease in price of an instrument. As the virtual instrument depends very little on dedicated hardware, a customer could now use his own computer, while an instrument manufacturer could supply only what the user could not get in the general market.

Virtual instrumentation combines mainstream commercial technologies, such as the PC, with flexible software and wide variety of measurement and control hardware, so engineers and scientists can create user defined system that meet their exact application needs. With Virtual instrumentation, engineers and scientist reduce development time, design higher quality products, and lower their design costs.

Virtual Instruments is basically used for displaying test or measurement data collected by the external device on instruments like panels on a computer screen. Thus Virtual Instrumentation uses a general purpose computer to mimic real instruments with their controls and displays.

The virtual instrument technology platform for the development of power quality monitoring system is flexible, easy to upgrade, able to overcome the traditional test and measurement system shortcomings, such as a single function and the complexity of the upgrade. Their functions are chosen by users and can be extended or modified according to users' requirements in contrast with traditional instrumentation (multimeters, oscilloscopes etc.) where the functions are vendor defined by hardware.

2.2 LITERATURE SURVEY ON DISTILLATION COLUMN CONTROL:

Jiann-Shiou Yang [1] developed the PI/PID control of a binary distillation column via a genetic searching algorithm (GSA). The time-domain design criterion, expressed as an integral of the squared error, is reformulated in the frequency-domain using the Parseval's relation and Padé approximation. A genetic algorithm is then used to search over the stability region in the controller parameter space for the best settings to minimize the design criterion.

Imam Makaremi [2] has presented a decentralized controller for a binary distillation column. The interactions between subsystems are considered as uncertainty. Then appropriate local H∞ problems are defined such that by solving them and applying the designed controller to the system, closed-loop stability and diagonal dominance are guaranteed.

Islam Mohamed Adel, Irraivan Elamvazuthi [3] has designed a model and simulated the control process of a binary methanol-water pilot plant and has analyzed the PI tuning techniques of Cohen-coon, Multi loop, Ziegler – Nichols and ITAE.

Raji P, Binu L S [4] have presented the application of sliding mode controller for a high purity binary distillation column. The main goal of the controller is to control the top and bottom product composition of a binary distillation column with high purity. They have used boilup rate V and the reflux rate R as the manipulated variables.

Ronia M. Oisiovici, Sandra L. Cruz [5] In this work, a linear time-varying state-space model for batch distillation columns was developed and tested. The model is suitable for on-line implementation and to predict the system behavior from measurable and easily available information. Comparing the model predictions with the rigorous simulation results, the state-space model was able to predict the batch distillation column behavior accurately, even for the nonideal mixture ethanol/water.

M. T. Tham [6] has presented the explanation and the various methods of distillation and components of the distillation column. In addition to that he has presented various distillation principles and the design of distillation column.

Vu Trieu Minh and Ahmed Majdi Abdul Rani [7] have introduced a calculation procedure for the modeling and control simulation of a condensate distillation column based on the energy balance (L-V) structure. In this control, the Reflux Rate L and the boilup Rate V are used as the inputs to the control the output of the purity of the distillate overhead and the impurity of the bottom products. The modeling simulation is important for process dynamic analysis and the plant initial design. This work has accomplished the modeling and simulation over three phases, nonlinear model of the plant, full order linearized model and the reduced order linear model. MRAC scheme has then been used for the controlling purposes.

J. Fernandez de Canete, P. Del Saz Orozco and S. Gonzalez-Perez [8] In this paper a LabVIEW environment has been employed as a graphical user interface for monitoring the

operation of a controlled distillation column, by visualizing both the closed loop performance and the user selected control conditions, while the column dynamics has been modeled under the SIMULINK environment. This tool has been applied to the PID based decoupled control of a binary distillation column.

Norrie and M. T. Tham have presented a detailed description of the distillation column components such as reflux drum, Tray types etc.

2.3 CONCLUSION: An extensive literature review of distillation column modeling and control using LabVIEW has been presented in this chapter.

CHAPTER III

Overview of labVIEW

3.1 VIRTUAL INSTRUMENTATION

Virtual instrumentation sets a new standard in measurement by replacing bench top instruments. It uses software like NI LabVIEW and hardware like PCI modules for data acquisition, instrument control and automation. VIs constructed with software are inexpensive, more accurate, maintenance free, can sense different physical quantities offering any range, compared to physical instruments. VIs works fast, handles repetitive tasks, processes data, stores results, generates reports, increases test safety and is controllable by the user. It saves time, money and increases productivity; customizability e.g. same code can be re-used for testing similar instruments. For any lab instead of buying individual instruments, VI can be employed in a computer for all measurements.

3.1.1 Virtual Instruments versus Traditional Instruments

Traditional instruments: Vendor defined, Function-specific; stand-alone with limited connectivity. Hardware is the key, Expensive, Closed, fixed functionality, slow turn on technology (5–10 year life Minimal economics of scale).

Virtual Instruments: User-defined, Application-oriented system with connectivity to networks, peripherals, and applications. Software is the key, low cost, reusable, Open, flexible functionality leveraging off familiar computer technology (Maximum economics of scale). Software minimizes development and maintenance costs.[11,15]

3.1.2 PROGRAMMING TECHNIQUES

LabVIEW programs are called virtual instruments or VIs, because their appearance and operation imitate physical instruments, such as oscilloscopes and millimeters. LabVIEW VIs contain three components: the front panel window, the block diagram, and the icon/connector pane.[11,15]

Front panel Window

The Front panel window is the user interface for the VI. Fig.3.2 shows example of a front panel window. We create the front panel window with controls and indicators, which are the interactive input and output terminals of the VI, respectively.

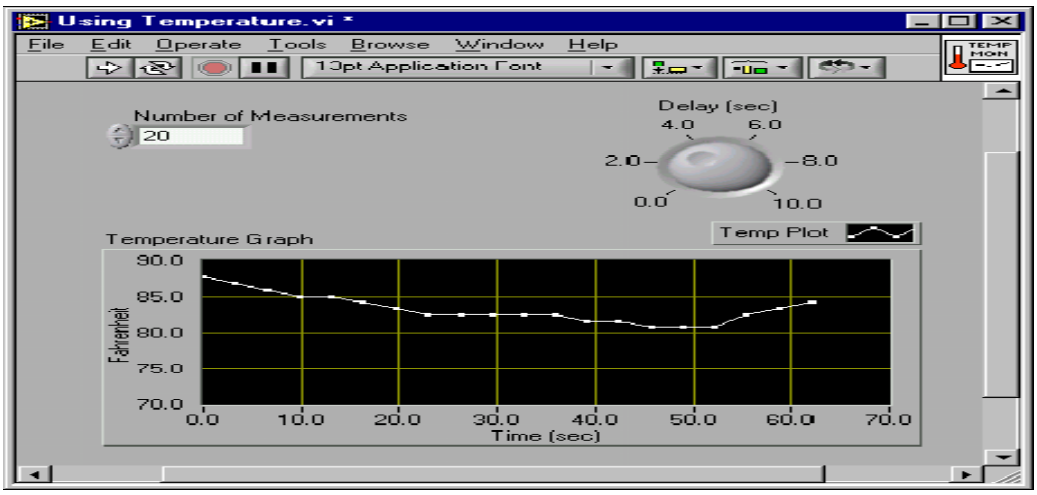

Fig.3.1 VI Front Panel

Block Diagram Window

After creating the Front Panel Window, we add code using graphical representation of functions to control the Front panel objects. Fig.3.3 shows an example of a block diagram window contains this graphical source code. Front panel objects appear as terminals on the block diagram.

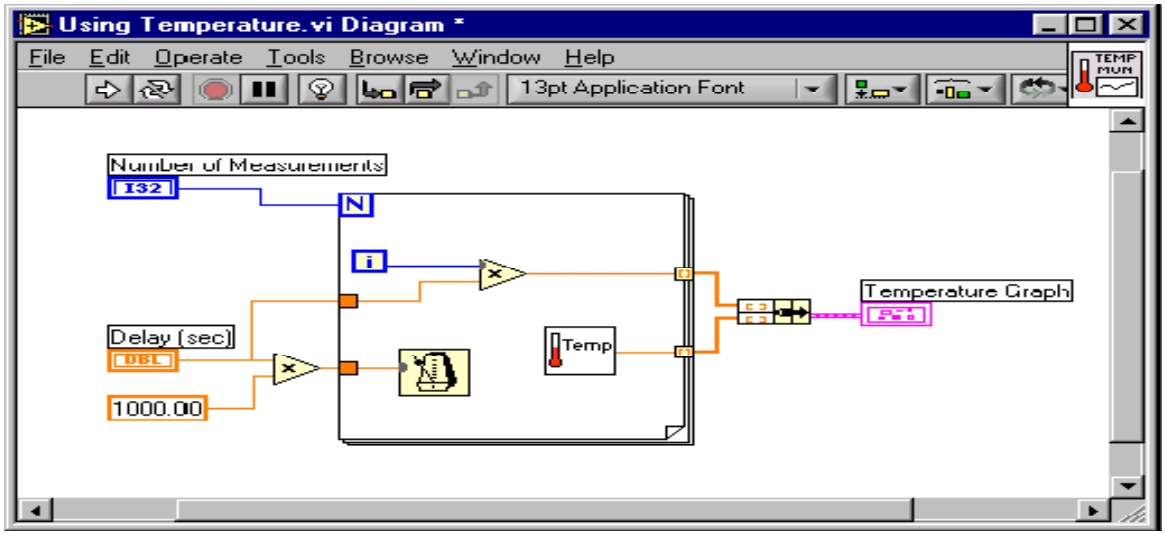

Fig. 3.2 VI Block Diagram

Icon and Connector Pane

A VI can be used as a **subVI.** A **subVI** is a VI that is used in another VI, similar to a function in a text based programming language. To use VI as a subVI, it must have an icon and connector Pane.

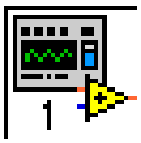

Fig. 3.3 Icon for SubVI

Every VI displays an icon, shown above, in the upper right corner of the front panel and block diagram windows. An icon is a graphical representation of a VI. It can contain text, images, or a combination of both. If we use a VI as a subVI, the icon identifies the subVI on the block diagram of the VI. The default icon contains a number that indicates how many new VIs we have opened since launching LabVIEW. Create custom icons to replace the default icon by right-clicking the icon in the upper right corner of the front panel or block diagram and selecting Edit Icon from the shortcut menu or by double-clicking the icon in the upper right corner of the front panel. We also can edit icons by selecting File»VI Properties, selecting General from the Category pull-down menu, and clicking the Edit Icon button. Use the tools on the left side of the Icon Editor Dialog box to create the icon design in the editing area. The normal size image of the icon appears in the appropriate box to the right of the editing area, as shown in the following dialog box in Fig.3.4.

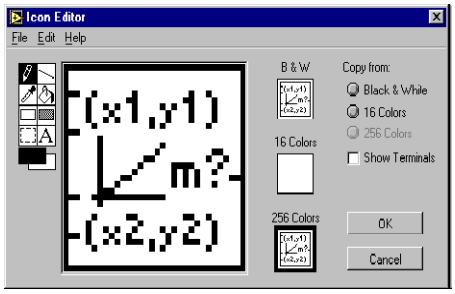

Fig. 3.4 Icon Editor

Use the options on the right side of the editing area to perform the following tasks:

- **Show Terminals**—Displays the terminal pattern of the connector pane.
- **OK**—Saves the drawing as the icon and returns to the front panel.
- **Cancel**—Returns to the front panel without saving any changes.

The menu bar in the **Icon Editor** dialog box contains more editing options such as **Undo**, **Redo**, **Cut**, **Copy**, **Paste**, and **Clear**.

 To use a VI as a **subVI**, we need to build a connector pane, shown at left. The connector pane is a set of terminals that corresponds to the controls and indicators of that VI, similar to the parameter list of a function call in text-based programming languages. The connector pane defines the inputs and outputs we can wire to the VI so we can use it as a subVI. Define connections by assigning a front panel control or indicator to each of the connector pane terminals. To define a connector pane, right-click the icon in the upper right corner of the front panel window and select **Show Connector** from the shortcut menu. The connector pane replaces the icon. Each rectangle on the connector pane represents a terminal. Use the rectangles to assign inputs and outputs. The number of terminals LabVIEW displays on the connector pane depends on the number of controls and indicators on the front panel. The following front panel has four controls and one indicator, so LabVIEW displays four input terminals and one output terminal on the connector pane**.** We cannot access the connector pane from the icon in the block diagram window.

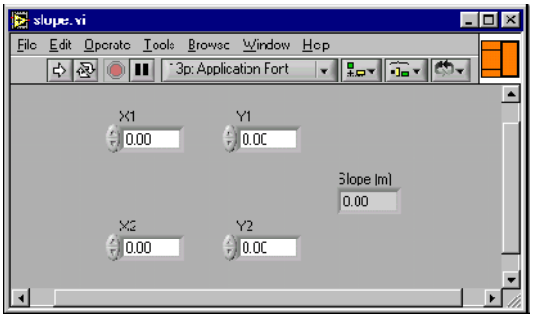

Fig. 3.5 icon/connector pane on top right side (orange colour box)

Palettes

LabVIEW has graphical, floating palettes to help you create and run VIs. The three palettes include the **Tools**, **Controls**, and **Functions** palettes. We can place these palettes anywhere on the screen.

Tools Palette

We can create, modify, and debug VIs using the tools located on the floating **Tools** palette. The **Tools** palette is available on the front panel and the block diagram. A tool is a special operating mode of the mouse cursor. When we select a tool, the cursor icon by itself changes to the tool

icon. Use the tools to operate and modify front panel and block diagram objects. Next select **Window»Show Tools Palette** to display the **Tools** palette. We can place the **Tools** palette anywhere on the screen. Press the <Shift> key and right-click to display a temporary version of the **Tools** palette at the location of the cursor.

Fig 3.6 Tools palette

 Use the Operating tool to change the values of a control or select the text within a control.

 Use the Positioning tool to select, move, or resize objects

 Use the Wiring tool to wire objects together on the block diagram.

Control and Function Palettes

The **Controls** and **Functions** contain sub-palettes of objects to create a VI. When click on sub-palette icon, the entire palette changes to the selected sub-palette. To use an object on the palettes, click the object and place it on the front panel or block diagram.

Controls Palette

Use the **Controls** palette to place controls and indicators on the front panel. The **Controls** palette is available only on the front panel. From there select **Window»Show Controls Palette** or right-click on the front panel workspace in order to display the **Controls** palette. We also can display the **Controls** palette by right-clicking an open area on the front panel. Tack down the **Controls** palette by clicking the pushpin on the top left corner of the palette.

Fig 3.7 Control Palette

Functions Palette

Use the **Functions** palette to build the block diagram. The **Functions** palette is available only on the block diagram. Select **Window»Show Functions Palette** or right-click the block diagram workspace to display the **Functions** palette. You also can display the **Functions** palette by right-clicking an open area on the block diagram. Tack down the **Functions** palette by clicking the pushpin on the top left corner of the palette.

Fig 3.8 Function palette

3.1.3 Starting a VI

When we launch LabVIEW, the following dialog box appears.

Fig 3.9 Start window that appears when labVIEW is launched

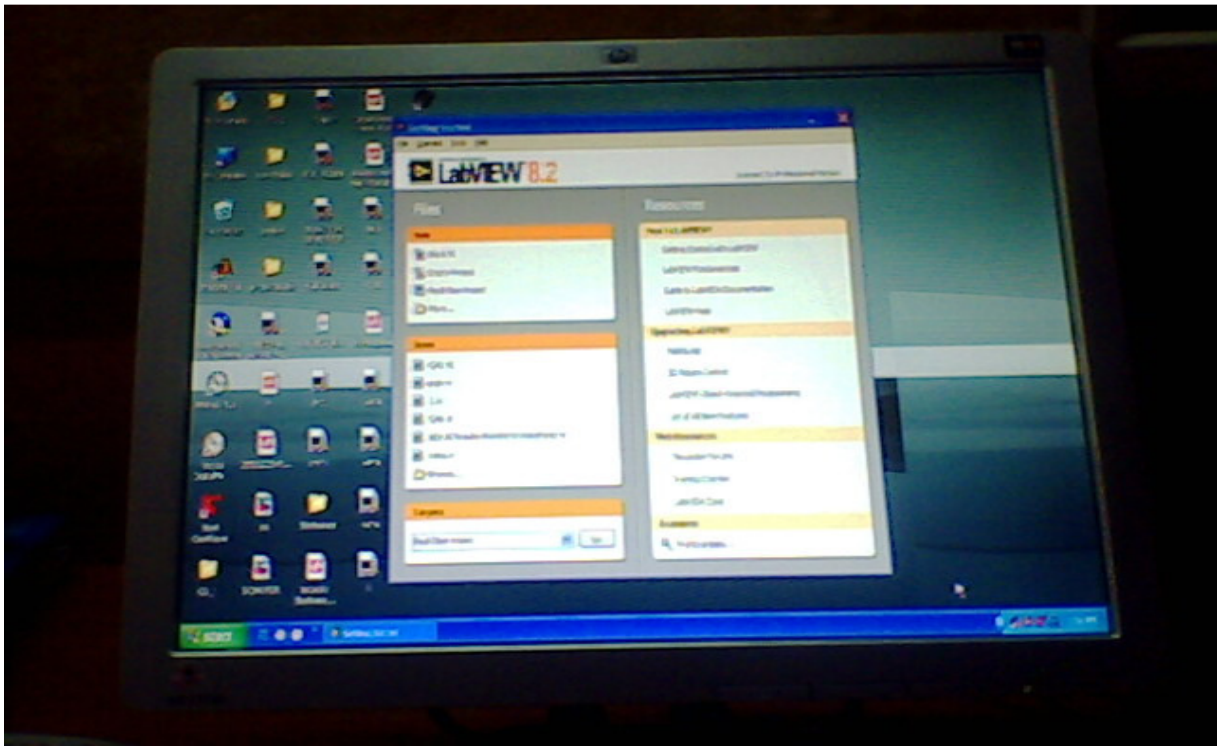

Fig 3.10 Dialog box for Getting Started of LabVIEW

The **LabVIEW** dialog box includes the following components:

• Click the **New VI** button to create a new VI.

• Click the **Open VI** button to open an existing VI.

• Click the **DAQ Solutions** button to launch the DAQ Solution Wizard, which helps we find solutions for common DAQ applications.

• Click the **Search Examples** button to open a help file that lists and links to all available

LabVIEW example VIs

• Click the **LabVIEW Tutorial** button to open the interactive LabVIEW Tutorial. Use this tutorial to learn basic LabVIEW concepts.

3.1.4 Troubleshooting and Debugging VIs

Use the Context Help window and the LabVIEW Help to help you build and edit VIs.

Context Help Window

To display the **Context Help** window, select **Help » Show Context Help** or press the <Ctrl-H>key. When we move the cursor over front panel and block diagram objects, the **Context Help** window displays the icon for sub VIs, functions, constants, controls and indicators, with wires attached to each terminal. When we move the cursor over dialog box options, the **Context Help** window displays descriptions of those options. In the window, required connections are bold, recommended connections are plain text, and optional connections are dimmed or do not appear. The following is an example **Context Help window.**

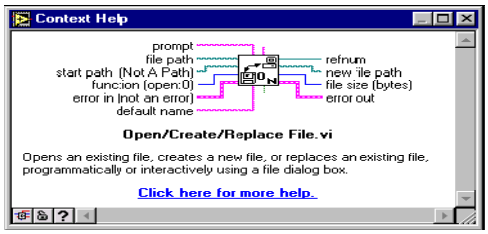

Fig. 3.11 shows Context Help

Click the **More Help** button to display the corresponding topic in the LabVIEW Help, which describes the object in detail.

3. 2 Advantages of VI:

Long before people used typewriters, which were then replaced by the word processors that offered new levels of productivity and flexibility. Much as the same way, VIs will replace the physical instruments.

Fig. 3.12 Comparison of the Virtual Instrument and Traditional Instrument

The picture on the top is that of a real instrument and the one on the bottom is that of a virtual one. Today's computer's graphic capabilities even make VIs look like real instruments. Virtual instruments are better connected to PC technologies widely used in industries. With VI, users can

move applications seamlessly between several bus architectures, such as PC Card, plug-in DA hardware, and VXI. This portability offers the flexibility to take advantage of improved bus standards as they arise.

3.2.1 Customizability VIs are fully customizable. Range, accuracy, amount of information provided by them can be selected by users. Data can be saved in computer and send it over the internet. They can be made to sense any physical quantity offering any range with the use of corresponding sensors. A VI can be made to control any other instruments including another VI.

3.2.2 Increases productivity VIs are less expensive and maintenance free. They work very fast, handle repetitive tasks, process data, store results and also generate reports. Reuse of code is also possible. Thus the same code can be used for testing similar instruments which saves time and money. Doing things in less time would definitely mean being able to do more. With less time, money and human labour for the same product, the productivity increases rapidly.

3.2.3 Lowers cost for customers Physical instruments are not suited for extreme weathers, but VIs can work in any hazardous environments. When a new product is tested using expensive test equipments, it naturally raises the overhead cost. Employing VI there reduces the testing cost. They also increase the test safety. They do not get damaged and thus no need of replacements. This lessens the price of the final product for customers.

3.2.4 User friendliness The software used for VI is user friendly. In LabVIEW, new users can step through the dialogue boxes and quickly build a fully functioning DA application. LabVIEW will help define signal types, connections, and transducer equations before building the system. Thus, the learning curve is shortened significantly. More experienced developers can use the DAQ Wizards to prototype a system.

Most VI system contains a microprocessor, a data-acquisition unit or system, an I/O port, a display or a way of reporting the results and an analysis engine. Since most of the hardware is the same, only the front-end of the device needs to be changed to suit the equipment's purpose. With a personal computer, software could do the analysis after acquiring the needed data. Thus, the software could be written as such to specifically answer what is called for by the analysis. The hardware could be changed according to the design of the experiment, whether it will receive data from an apparatus or control it. Instead of using separate hardware front-ends, software could be written for measuring different quantities. Thus with sensors and appropriate software, any physical quantity can be acquired and measured in VI.

Some other applications of VI are data analysis, systems control, process automation, testing and calibration of instruments, telecommunications, semiconductor manufacturing, automotive testing, robotics, automation, embedded systems, etc.

3.3 CONCLUSION

The future of virtual instrumentation is promising. As such companies as Intel and Microsoft continue to usher in new technologies for advanced productivity and connectivity; virtual instrumentation's benefits will increase. Improvements in PC technology and VI hardware and software will make new applications possible. Companies like National Instruments are promoting VI to make it reach everyone. Quite sooner the traditional instrumentation will be completely moved inside the computer.

CHAPTER IV

INTRODUCTION TO DISTILLATION PROCESS

4.1 INTRODUCTION: Distillation is the very basic and common process in the chemical and in petroleum industries. It is used for separating feed streams and for purification of final and intermediate product streams. More precisely it can be defined as,

"A process in which a liquid or vapour mixture of two or more substances is separated into its component fractions of desired purity, by the application and removal of heat."[1][14]

4.1.1 BASIC PRINCIPLE OF DISTILLATION PROCESS:

Distillation is based on the fact that the vapour of a boiling mixture will be richer in the components that have lower boiling points. Therefore, when this vapour is cooled and condensed, the condensate will contain more volatile components. At the same time, the original mixture will contain more of the less volatile material. Distillation columns are designed and controlled to achieve this separation efficiently. Although many people have a fair idea what "distillation" means, the important aspects that seem to be missed from the manufacturing point of view are that: Distillation is the most common separation technique and it consumes enormous amounts of energy, both in terms of cooling and heating requirements. It can contribute to more than 50% of plant operating costs. The best way to reduce operating costs of existing units, is to improve their efficiency and operation via process optimization and control. To achieve this improvement, a thorough understanding of distillation principles and how distillation systems are designed is essential [14].

4.2 HISTORICAL ASPECTS OF DISTILLATION:

The first clear evidence of distillation comes from Greek alchemists working in Alexandria in the first century AD[16]. Distilled water has been known since at least ca. 200 AD, when Alexander of Aphrodisias described the process [17]. Clear evidence of the distillation of alcohol comes from the School of Salerno in the 12th century [16][18].**Fractional distillation** was developed by Tadeo Alderotti in the 13th century [19] . In 1500, German alchemist Hieronymus

Braunschweig published 'Liber de arte destillandi' (The Book of the Art of Distillation) the first book solely dedicated to the subject of distillation, followed in 1512 by a much expanded version. In 1651, John French published, The Art of Distillation, the first major English compendium of practice, though it has been claimed [20] that much of it derives from Braunschweig's work. This includes diagrams with people in them showing the industrial rather than bench scale of the operation. As alchemy evolved into the science of chemistry, vessels called **'retorts'** became used for distillations. Both alembics and retorts are forms of glassware with long necks pointing to the side at a downward angle which acted as air-cooled condensers to condense the distillate and let it drip downward for collection. Later, copper alembics were invented. Riveted joints were often kept tight by using various mixtures, for instance a dough made of rye flour.

Fig. 4.1 A Retort

These alembics often featured a cooling system around the beak, using cold water for instance, which made the condensation of alcohol more efficient. These were called pot stills. Today, the retorts and pot stills have been largely supplanted by more efficient distillation methods in most industrial processes. However, the pot still is still widely used for the elaboration of some fine alcohols such as cognac. Pot stills made of various materials (wood, clay, stainless steel) are also used by bootleggers in various countries. Small pot stills are also sold for the domestic production of flower water or essential oils. Early forms of distillation were batch processes using one vaporization and one condensation. Purity was improved by further distillation of the condensate.

Fig. 4.2 An earlier method for Distillation

Greater volumes were processed by simply repeating the distillation. Chemists were reported to carry out as many as 500 to 600 distillations in order to obtain a pure compound. In the early 19th century the basics of modern techniques including pre-heating and reflux were developed, particularly by the French, and then in 1830 a British Patent was issued to Aeneas Coffey for a whiskey distillation column, which worked continuously and may be regarded as the archetype of modern petrochemical units. In 1877, Ernest Solvay was granted a U.S. Patent for a tray column for ammonia distillation and the same and subsequent years saw developments of this theme for oil and spirits. With the emergence of chemical engineering as a discipline at the end of the 19th century, scientific rather than empirical methods could be applied. The developing petroleum industry in the early 20th century provided the impetus for the development of accurate design methods such as the **McCabe-Thiele** method and the **Fenske equation**. In present era the availability of powerful computers has also allowed direct computer simulation of distillation columns.

4.3 TYPES OF DISTTILLATION PROCESS:

There are two major types of distillation processes i.e.,

4.3.1 **Batch Distillation**: In batch operation, the feed to the column is introduced batch-wise. That is, the column is charged with a 'batch' and then the distillation process is carried out. When the desired task is achieved, a next batch of feed is introduced [2]. Heating an ideal mixture of two volatile substances A and B (with A having the higher volatility, or lower boiling point) in a batch distillation setup (such as in an apparatus depicted in the following figure)

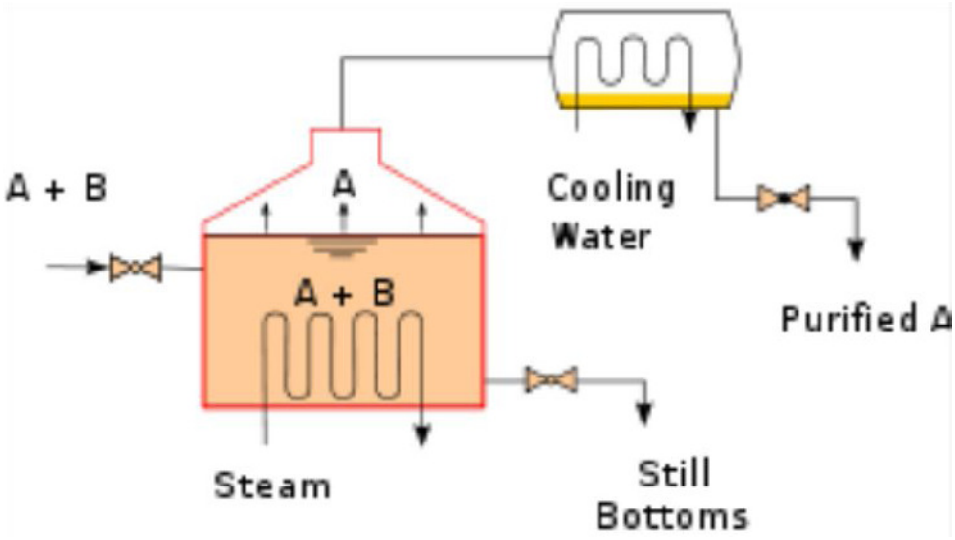

Fig. 4.3 Basic Distillation Process

until the mixture is boiling results in a vapor above the liquid which contains a mixture of A and B. The ratio between A and B in the vapor will be different from the ratio in the liquid: the ratio in the liquid will be determined by how the original mixture was prepared, while the ratio in the vapor will be enriched in the more volatile compound, A (due to Raoult's Law, see above). The vapor goes through the condenser and is removed from the system. This in turn means that the ratio of compounds in the remaining liquid is now different from the initial ratio (i.e. more enriched in B than the starting liquid). The result is that the ratio in the liquid mixture is changing, becoming richer in component B. This causes the boiling point of the mixture to rise, which in turn results in a rise in the temperature in the vapor, which results in a changing ratio of A : B in the gas phase (as distillation continues, there is an increasing proportion of B in the gas phase). This results in a slowly changing ratio A : B in the distillate. If the difference in vapor pressure between the two components A and B is large (generally expressed as the difference in boiling points), the mixture in the beginning of the distillation is highly enriched in component A, and when component A has distilled off, the boiling liquid is enriched in component B.

This type of distillation is generally used in Laboratory scale Distillation, since the product of the process is in little amount. **Laboratory scale distillations** are of different types, such as,

(i) **Simple Distillation**: In simple distillation, all the hot vapors produced are immediately channeled into a condenser that cools and condenses the vapors. Therefore, the distillate will not be pure – its composition will be identical to the

composition of the vapors at the given temperature and pressure, and can be computed from Raoult's law. As a result, simple distillation is usually used only to separate liquids whose boiling points differ greatly (rule of thumb is 25 °C), or to separate liquids from involatile solids or oils. For these cases, the vapor pressures of the components are usually sufficiently different that Raoult's law may be neglected due to the insignificant contribution of the less volatile component. In this case, the distillate may be sufficiently pure for its intended purpose.

(ii) **Fractional distillation:** For many cases, the boiling points of the components in the mixture will be sufficiently close that Raoult's law must be taken into consideration. Therefore, **fractional distillation** must be used in order to separate the components well by repeated vaporization-condensation cycles within a packed fractionating column. This separation, by successive distillations, is also referred to as **rectification**.[21] As the solution to be purified is heated, its vapors rise to the fractionating column. As it rises, it cools, condensing on the condenser walls and the surfaces of the packing material. Here, the condensate continues to be heated by the rising hot vapors; it vaporizes once more. However, the compositions of the fresh vapors are determined once again by Raoult's law. Each vaporization-condensation cycle (called a *theoretical plate*) will yield a purer solution of the more volatile component. In reality, each cycle at a given temperature does not occur at exactly the same position in the fractionating column; *theoretical plate* is thus a concept rather than an accurate description. More theoretical plates lead to better separations. A spinning band distillation system uses a spinning band of Teflon or metal to force the rising vapors into close contact with the descending condensate, increasing the number of theoretical plates.

(iii) **Steam distillation:** Like vacuum distillation, **steam distillation** is a method for distilling compounds which are heat-sensitive.[22] This process involves bubbling steam through a heated mixture of the raw material. By Raoult's law, some of the target compound will vaporize (in accordance with its partial pressure). The vapor mixture is cooled and condensed, usually yielding a layer of oil and a layer of water.

Steam distillation of various aromatic herbs and flowers can result in two products; an essential oil as well as a watery herbal distillate. The essential oils are often used in perfumery and aromatherapy while the watery distillates have many applications in aromatherapy, food processing and skin care.

(iv) **Vacuum distillation:** Some compounds have very high boiling points. To boil such compounds, it is often better to lower the pressure at which such compounds are boiled instead of increasing the temperature. Once the pressure is lowered to the vapor pressure of the compound (at the given temperature), boiling and the rest of the distillation process can commence. This technique is referred to as **vacuum distillation** and it is commonly found in the laboratory in the form of the rotary evaporator. This technique is also very useful for compounds which boil beyond their decomposition temperature at atmospheric pressure and which would therefore be decomposed by any attempt to boil them under atmospheric pressure.

(v) **Molecular distillation:** Molecular distillation is vacuum distillation below the pressure of 0.01 torr. 0.01 torr is one order of magnitude above high vacuum, where fluids are in the free molecular flow regime, i.e. the mean free path of molecules is comparable to the size of the equipment. The gaseous phase no longer exerts significant pressure on the substance to be evaporated, and consequently, rate of evaporation no longer depends on pressure. That is, because the continuum assumptions of fluid dynamics no longer apply, mass transport is governed by molecular dynamics rather than fluid dynamics. Thus, a short path between the hot surface and the cold surface is necessary, typically by suspending a hot plate covered with a film of feed next to a cold plate with a line of sight in between. Molecular distillation is used industrially for purification of oils.

4.3.2 **Continuous distillation:** Continuous distillation processes a continuous feed stream. No interruptions occur unless there is a problem with the column or surrounding process units. They are capable of handling high throughputs and are the more common of the two types i.e. among batch and continuous distillation. Industrial distillation comes under the category of continuous distillation. In this dissertation only continuous distillation is modeled and controlled.

(i) **Industrial Distillation:** Large scale **industrial distillation** applications include both batch and continuous fractional, vacuum, azeotropic, extractive, and steam distillation. The most widely used industrial applications of continuous, steady-state fractional distillation are in petroleum refineries, petrochemical and chemical plants and natural gas processing plants. Industrial distillation[21][23] is typically performed in large, vertical cylindrical columns known as **distillation towers** or **distillation columns** with diameters ranging from about 65 centimeters to 16 meters and heights ranging from about 6 meters to 90 meters or more. When the process feed has a diverse composition, as in distilling crude oil, liquid outlets at intervals up the column allow for the withdrawal of different *fractions* or products having different boiling points or boiling ranges. The "lightest" products (those with the lowest boiling point) exit from the top of the columns and the "heaviest" products (those with the highest boiling point) exit from the bottom of the column and are often called the **bottoms.** Industrial towers use reflux to achieve a more complete separation of products. Reflux refers to the portion of the condensed overhead liquid product from a distillation or fractionation tower that is returned to the upper part of the tower as shown in the schematic diagram of a typical, large-scale industrial distillation tower. Inside the tower, the down flowing reflux liquid provides cooling and condensation of the up flowing vapors thereby increasing the efficiency of the distillation tower. The more reflux that is provided for a given number of theoretical plates, the better the tower's separation of lower boiling materials from higher boiling materials. Alternatively, the more reflux that is provided for a given desired separation, the fewer the number of theoretical plates required. Such industrial fractionating towers are also used in air separation, producing liquid oxygen, liquid nitrogen, and high purity argon. Distillation of chlorosilanes also enables the production of high purity silicon for use as a semiconductor. Design and operation of a distillation tower depends on the feed and desired products. Given a simple, binary component feed, analytical methods such as the McCabe-Thiele method [21][24] or the Fenske equation[21] can be used. For a multi component feed, simulation models are used both for design and operation. Moreover, the efficiencies of the vapor-liquid contact devices (referred to as "plates" or "trays") used in distillation towers are typically

lower than that of a theoretical 100% efficient equilibrium stage. Hence, a distillation tower needs more trays than the number of theoretical vapor-liquid equilibrium stages. In modern industrial uses, generally a packing material is used in the column instead of trays, especially when low pressure drops across the column are required, as when operating under vacuum. This packing material can either be random dumped packing (1-3" wide) such as Raschig rings or structured sheet metal. Liquids tend to wet the surface of the packing and the vapors pass across this wetted surface, where mass transfer takes place. Unlike conventional tray distillation in which every tray represents a separate point of vapor-liquid equilibrium, the vapor-liquid equilibrium curve in a packed column is continuous. However, when modeling packed columns, it is useful to compute a number of "theoretical stages" to denote the separation efficiency of the packed column with respect to more traditional trays. Differently shaped packings have different surface areas and void space between packings. Both of these factors affect packing performance. Another factor in addition to the packing shape and surface area that affects the performance of random or structured packing is the liquid and vapor distribution entering the packed bed. The number of theoretical stages required to make a given separation is calculated using a specific vapor to liquid ratio. If the liquid and vapor are not evenly distributed across the superficial tower area as it enters the packed bed, the liquid to vapor ratio will not be correct in the packed bed and the required separation will not be achieved. The packing will appear to not be working properly. The height equivalent of a theoretical plate (HETP) will be greater than expected. The problem is not the packing itself but the mal-distribution of the fluids entering the packed bed. Liquid mal-distribution is more frequently the problem than vapor. The design of the liquid distributors used to introduce the feed and reflux to a packed bed is critical to making the packing perform to it maximum efficiency. Methods of evaluating the effectiveness of a liquid distributor to evenly distribute the liquid entering a packed bed can be found in references.

Fig. 4.4 A Typical Industrial Distillation Column

Industrial distillation is typically performed in large, vertical cylindrical columns (as shown in Figure) known as "distillation towers" or "distillation columns" with diameters ranging from about 65 centimeters to 6 meters and heights ranging from about 6 meters to 60 meters or more. Industrial distillation towers are usually operated at a continuous steady state. Unless disturbed by changes in feed, heat, ambient temperature, or condensing, the amount of feed being added normally equals the amount of product being removed. It should also be noted that the amount of heat entering the column from the reboiler and with the feed must equal the amount heat removed by the overhead condenser and with the products. Figure 3 depicts an industrial fractionating column separating a feed stream into one distillate fraction and one bottoms fraction.

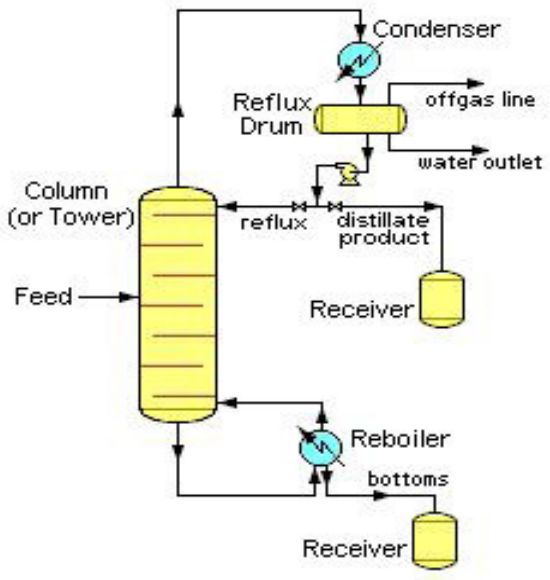

Fig. 4.5 Schematic Diagram of Binary Distillation Column

However, many industrial fractionating columns have outlets at intervals up the column so that multiple products having different boiling ranges may be withdrawn from a column distilling a multi-component feed stream. The "lightest" products with the lowest boiling points exit from the top of the columns and the "heaviest" products with the highest boiling points exit from the bottom. Industrial fractionating columns use external reflux to achieve better separation of products.[26][21] Reflux refers to the portion of the condensed overhead liquid product that returns to the upper part of the fractionating column as shown in Figure 3. Inside the column, the downflowing reflux liquid provides cooling and condensation of upflowing vapors thereby increasing the efficacy of the distillation tower. The more reflux and/or more trays provided, the better is the tower's separation of lower boiling materials from higher boiling materials. The design and operation of a fractionating column depends on the composition of the feed and as well as the composition of the desired products. Given a simple, binary component feed, analytical methods such as the McCabe-Thiele method [21][27][28] or the Fenske equation[21] can be used. For a multi-component feed, simulation models are used both for design, operation and construction. Bubble-cap "trays" or "plates" are one of the types of physical devices which are used to provide good contact between the up flowing vapor and the down flowing liquid inside an industrial fractionating column. Such trays are shown in Figures 4 and 5. The efficiency of a tray or plate is typically lower than that of a theoretical 100% efficient

equilibrium stage. Hence, a fractionating column almost always needs more actual, physical plates than the required number of theoretical vapor-liquid equilibrium stages.

4.4 DISTILLATION COLUMN/TOWER:

Distillation columns or towers are constructed to behave in the same way as a series of separate stills as discussed earlier. Each 'still' section consists of a number of 'TRAYS' or contacting devices arranged vertically above one another in the column. These trays or contactors bring liquid and vapour into intimate contact in order to obtain the required separation of the mixture. The height of the tower and the number of trays or contacting devices it contains depends upon the purity of the 'Fractions' required. Columns for the distillation process can be of the following types:

1. The 'PACKED' Tower
2. The 'TRAY' Tower

4.4.1 PACKED TOWER:

As its name implies, the packed tower is a vertical, steel column which contains 'Beds' of packing material which are used to bring the rising vapours into intimate contact with falling liquid within the tower. The heat added to the mixture before entering the tower partially vaporises the mixture and the vapours rise up the tower and begin to cool. The liquid falls towards the bottom of the tower. At the tower bottom, in general, more heat is added to the liquid by a 'Reboiler' which may be steam heated or a fuel fired furnace type. The addition of heat here causes more vapours to rise up the column. As the two phases of the mixture - falling liquid and rising vapour - come together, light components are stripped out of the liquid and enter the gas phase while heavy components in the vapour are condensed into the liquid phase. In this way, as the vapour rises and gradually cools, it becomes lighter and, as the liquid falls, it becomes hotter and heavier. With this type of distillation column there is generally only a top and bottom product. The quality of the products depends upon the height of the tower, the number of contacting devices, the tower temperature and pressure and their control, and the velocity of the rising vapours. The type of packing materials used, also plays a part in the separation process. The

packing can be of such types as, Ceramic Raschig Rings, Stainless Steel Pall Rings or Ceramic Saddles.

4.4.2 TRAY TYPE TOWER: This is also a tall, cylindrical column. Inside, a series of trays are placed, one above the other. The trays are used to bring the rising vapour and falling liquid into intimate contact. Tray towers do the same job as packed towers but they are very much more efficient in the separation process than packed towers and, they are also more costly. There are various types of tray in use and the type selected depends upon the degree of product purity required, the type of fluids, fluid velocity and other process parameters of the system.

The types of tray used in distillation columns are as follows:

(a) THE SIEVE TRAY is simply a metal plate containing drilled holes through which the rising vapour can pass into the liquid flowing across the tray.

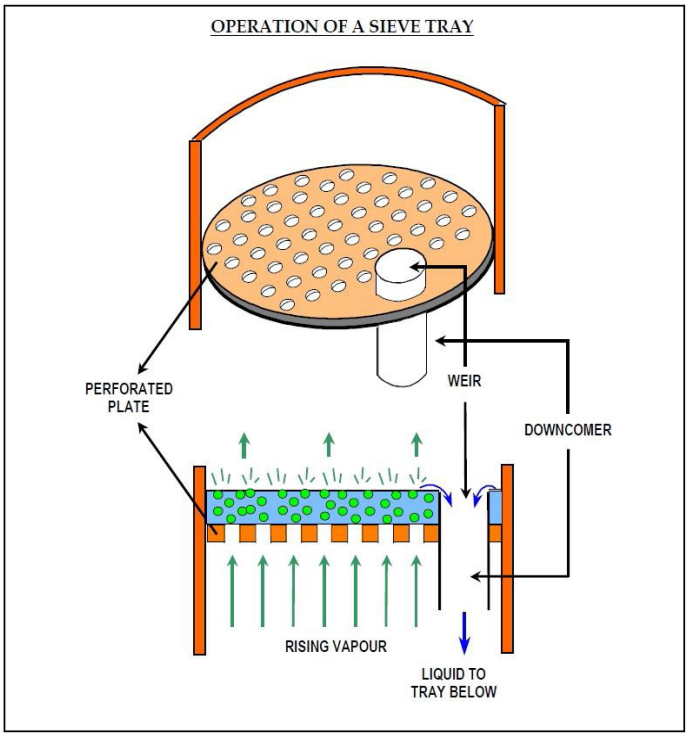

Fig. 4.6 Sieve Tray

(b) THE VALVE TRAY is similar to the sieve type but, each hole is fitted with a flapper valve which opens as vapour passes through the hole. This type is used where vapour velocity is not constant and the valves prevent liquid from dumping through the holes at times of low gas velocity.

(c) THE BUBBLE-CAP TRAY is the most efficient separation device but, is also the most costly. It consists of a number of 'Chimneys' or 'Risers' (small, short pipes set into the tray), through which the vapour can pass. Fitted over the riser is a 'Cap' which causes the rising vapour to turn through 180 °. This forces the gas to 'Bubble' through the liquid flowing across the tray. The liquid level on the tray is maintained below the top of the riser to prevent dumping of liquid down the tower.

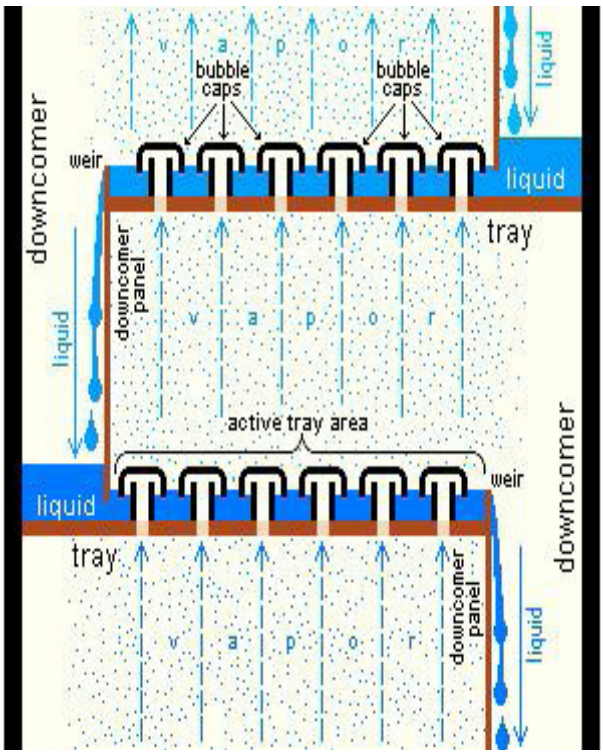

Fig. 4.7 Bubble Cap Tray

Each of the above trays also has a 'WEIR' that maintains the liquid level on the tray. As the liquid flows over the weir, it enters a 'DOWNCOMER' - (a short pipe), that carries the liquid down to the tray below. The downcomer outlet is below the surface of the liquid on the tray below, acting as a seal to prevent gas from bypassing the tray above.

4.5 BASIC CONTINUOUS DISTILLATION PROCESS FOR PETROLEUM INDUSTRIES: Figure 4.8 represents a basic Crude Oil distillation column where the feed to, and the products from, the unit is a continuous operation. In the distillation process, the crude oil feed is first heated by exchanging heat with some of the hot products leaving the column. This cools the products and, at the same time reduces the fuel requirements in the main heater - the fuel fired furnace. The hot feed now enters the tower into the **'Flash Zone'**. At this point, due to the greatly increased volume of the column, the lighter components of the crude oil **' Flash Off '** (vaporise), and rise up the column. The hot liquid will fall towards the column bottom. The bottom section of the column, below the Flash Zone, called the **'Stripping Section'**, contains trays – generally Bubble-cap or Sieve type. The tower bottom liquid is re-circulated & re-heated in a steam or fired 'Reboiler' which drives off vapours of light ends and some of the heavy ends contained in the liquid. These vapours rise upwards through the trays and contact the down-flowing liquid. This action further removes (strips out), light ends from the liquid. The top section of the tower, above the flash zone, is called the **'Rectifying Section'**. Here again, the rising vapour passing through the trays, contacts the liquid flowing across them.

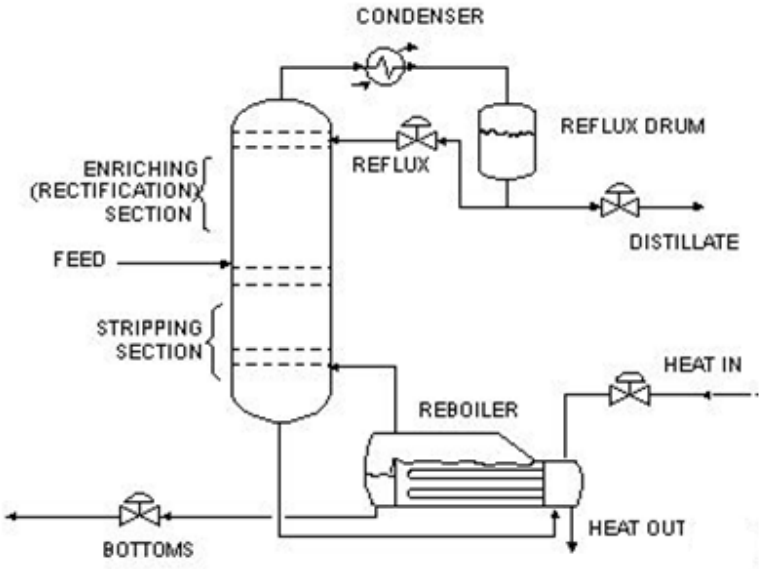

Fig. 4.8 Different Sections and Components of Distillation Column

4.5.1 Action of the Trays: Each tray in the tower is acting like a single still as discussed in 'Batch Distillation'. As we rise above the flash zone, each succeeding tray is slightly cooler than the tray below. The down-flowing liquid, as it passes across the trays is becoming hotter and heavier as light ends boil off into the vapour phase. Conversely, the rising vapour is becoming cooler and lighter as heavier ends condense into the liquid on the tray. The down-flowing liquid is called 'Internal Reflux' where the liquid is returned to the preceding still. At pre-determined points in the column, the process conditions (mainly temperature and pressure), are such that, the liquid components are at the required purity to meet the specification desired as a product – like 'Kerosene' for example. At these points, the tower will contain **'Collecting Pans**' from which the desired product can be drawn from the tower.

4.6 CONCLUSION: This chapter has dealt with the basic distillation process and the components of the distillation column.

CHAPTER V
MATHEMATICAL MODELING AND CONLTROL OF DISTILLATION PROCESS/COLUMN

5.1 INTRODUCTION: Various processes are involved in the industries and to make them efficient, controlling of these processes has to be done. Various control strategies are employed for the purpose. The plant, control system, actuator, feedback devices, Sensor, in whole, completes a process control system. Application of the control system to a plant is a two sided sword; the whole system can become unstable or inefficient if the control system is not appropriately designed. Since the components of the control system are very expensive, and design of the control system is a time consuming process, it makes real time testing of the application of the control system practically impossible. Thus an alternative technique exists in which the equations which govern the plant behavior is first stated and then transfer equation which relate the plant output and the input is build. The controller is then designed mathematically and then analyzed, with various testing tool available such as root locus techniques, Nyquist criterion, Routh Hurwitz method, Bode Plot analysis, for the various performance criterions. One of the most important tasks in the analysis and design of control system is **Mathematical Modeling** of the systems. The most common methods of the modeling of the linear systems are Transfer Function approach and the State Equation approach. The Transfer function approach is valid only for the linear system and the state equation approach is valid for both, i.e., linear as well as non-linear systems. In reality, since all physical systems are non-linear to some extent, in order to use transfer functions and linear state equations the system must first be linearized, or its range of operation be confined to a linear range.

Although the analysis and design of linear control system have been well developed, their counter parts for non-linear systems are usually quite complex. Therefore, the control systems engineer often has the task of determining not only how to accurately describe a syatem mathematically, but more importantly, how to make proper assumptions and approximations, whenever necessary, so that the system may be adequately characterized by a linear mathematical model [29].

5.2 MODELING OF DISTILLATION COLUMN: Distillation column, as described earlier is a long tower comprising of several components, which are responsible for the energy and mass transfer, such as, [9]

1. Trays (or stills), to enhance component separations,
2. Reboiler, to provide necessary heat for vaporization for the distillation process,
3. Condensor, to cool and condense the vapour leaving the top of the column
4. Reflux Drum, to hold the condensed vapour from the top of the column so that a part of that liquid can be fed back (Reflux) to the column,

and some other components to enhance the efficiency of the column and hence the whole process.

These basic components stated above indulge in the vapour and liquid mixing and transfer of the mass and energy from one stage to another. This energy and mass transfer can be modeled using differential equations.

This dissertation only deals with binary distillation column model. To model a binary distillation column, there are namely following components,

1. Reflux drum
2. Condensor
3. Top Tray
4. Rectification zone trays
5. Feed Tray
6. Stripping zone trays
7. Bottom Tray
8. Column Base and Reboiler.

To model this system some assumptions have been used, such as, the binary system (two components) has constant relative volatility throughout the column and theoretical (100% efficient) trays. A 100% efficient tray is a tray, in which vapour leaving a tray is in equilibrium with the liquid on the tray. So, the simple vapour liquid equilibrium is used,

$$y_n = \frac{\alpha x_n}{1 + (\alpha - 1)x_n} \qquad -(5.1)$$

Where,

x_n = Liquid composition on the nth tray (mole fraction more volatile component)

y_n = Vapour composition on the nth tray (more fraction more volatile component)

α = Relative volatility.

A single feed stream is fed as saturated liquid (at its bubble point) onto the feed tray N_F. Feed flow rate is F (mol/min) and composition is z (mole fraction more volatile component). The overhead vapour is totally condensed in condenser and flows into the reflux drum, whose holdup of liquid is M_D (moles). The contents of the drum is assumed to be perfectly mixed with composition x_D. The liquid in the drum is at its bubblepoint. Reflux is pumped back to the top tray (N_T) of the column at the rate L. Overhead distillate product is removed at a rate D.

Any delay time is neglected (dead time) in the vapour line from the top of the column to the reflux drum and in the reflux line back to the top tray. The vapour content at the top tray y_{NT} is not equal , dynamically, to x_D. These two components are equal only at the steady state.

At the base of the column, the liquid bottom product is removed at a rate B and with a composition x_B. Vapour boilup is generated in a thermosiphon reboiler at a rate V. Liquid circulates from the bottom of the column through the tubes in the vertical tube-in-shell reboiler because of the smaller density of the vapour liquid mixture in the reboiler tubes. It is assumed that the liquids in the reboiler and in the base of the column are perfectly mixed together and have the same composition x_B and holdup M_B (moles). The circulation rates through well-designed thermosiphon reboilers are quite high, so this assumption is applicable here. The composition of the vapor leaving the base of the column and entering tray 1 is Y_B. It is in equilibrium with the liquid having composition x_B.

The column contains a total of N_T theoretical trays. The liquid holdup on each tray including the downcomer is M_n. The liquid on each tray is assumed to be perfectly mixed with composition x_n. The holdup of the vapor is assumed to be negligible throughout the system. Although the vapour volume is large, the number of moles is usually small because the vapor density is so much smaller than the liquid density. This assumption brakes down in high-pressure columns.

A further assumption taken is that of equimolal overflow. If the molar heats of the vaporization of the two components are about the same, whenever one mole of vapor condenses, it vaporizes a mole of liquid. Heat losses up the column and temperature changes from tray to tray (sensible-heat effects) are assumed negligible. These assumptions mean that the vapor rates through the stripping section and the rectifying sections will be constant under the steady state conditions.

The assumption above stated, including negligible vapour holdup, mean that the vapour rate through all trays of the column is the same, dynamically as well as at steady state.

$$V = V_1 = V_2 = V_3 = ... = V_{NT} \qquad \text{- (5.2)}$$

These vapour holdups are equal only at the steady state and are not necessarily constant with the time. The vapour boilup can be manipulated dynamically. The mathematical effect of assuming equimolal overflow is that, modeling doesn't need an energy equation for each tray.

The liquid rates is not same throughout the column, they will depend on the fluid dynamics of the tray. A simple Francis Weir formula relationship has been used to relate the liquid holdup on the tray (M_n) to the liquid flow rate leaving the tray (L_n).

$$F_L = 3.33 L_w (h_{ow})^{1.5} \qquad -(5.3)$$

Where,

F_L = liquid flow rate over weir (ft^3/sec)

L_W = length of weir (ft)

h_{ow} = height of liquid over weir (ft).

One more assumption which has been made is neglecting the dynamics of the condenser and the reboiler. Since, in continuous type columns the, dynamic response of these heat exchangers is usually much faster than the response of the column itself.

5.2.1Differential Equations related to Differential column: Taking all the above assumptions, now the equations which describe the system can be stated as,

Condenser and Reflux Drum:

Total Continuity:

$$\frac{dM_D}{dt} = V - (L + D) \qquad -(5.4)$$

Component Continuity (more volatile component):

$$\frac{d(M_D x_D)}{dt} = Vy_{NT} - (L + D)x_D \qquad -(5.5)$$

Top Tray (n = N_T):

Total Continuity:

$$\frac{dM_{NT}}{dt} = L - L_{NT} \qquad -(5.6)$$

Component Continuity (more volatile component):

$$\frac{d(M_{NT}x_{NT})}{dt} = Lx_D - L_{NT}\,x_{NT} + Vy_{NT-1} - Vy_{NT} \qquad -(5.7)$$

Next to Top Tray (n = N_T -1):

Total Continuity:

$$\frac{dM_{NT-1}}{dt} = L_{NT} - L_{NT-1} \qquad -(5.8)$$

Component Continuity (more volatile component):

$$\frac{d(M_{NT-1}x_{NT-1})}{dt} = L_{NT}\,x_{NT} - L_{NT-1}\,x_{NT-1} + Vy_{NT-2} - Vy_{NT-1} \qquad -(5.9)$$

n^{th} Tray:

Total Continuity:

$$\frac{dM_n}{dt} = L_{n+1} - L_n \qquad -(5.10)$$

Component Continuity (more volatile component):

$$\frac{d(M_n x_n)}{dt} = L_{n+1}\, x_{n+1} - L_n\, x_n + Vy_{n-1} - Vy_n \qquad -(5.11)$$

Feed Tray (at n= N_F):

Total Continuity:

$$\frac{dM_{NF}}{dt} = L_{NF+1} - L_{NF} + F \qquad -(5.12)$$

Component Continuity (more volatile component):

$$\frac{d(M_{NF} x_{NF})}{dt} = L_{NF+1}\, x_{NF+1} - L_{NF}\, x_{NF} + Vy_{NF-1} - Vy_{NF} + Fz \qquad -(5.13)$$

First Tray:

Total Continuity:

$$\frac{dM_1}{dt} = L_2 - L_1 \qquad -(5.14)$$

Component Continuity (more volatile component):

$$\frac{d(M_1 x_1)}{dt} = L_2\, x_2 - L_1\, x_1 + Vy_b - Vy_1 \qquad -(5.15)$$

Reboiler & Column Base:

Total Continuity:

$$\frac{dM_B}{dt} = L_1 - V - B \qquad -(5.16)$$

Component Continuity (more volatile component):

$$\frac{d(M_B x_B)}{dt} = L_1 x_1 - V y_b - B x_B \qquad -(5.17)$$

Based on above equations, the mathematical model of the distillation column has been designed in the LabVIEW. Top product (Distillate) composition and the bottom product composition are the output i.e. Controlled variables of the plant system, and the manipulate variables are the Reflux Rate (L) and the Vapour Boilup Rate (V).

5.3 INTRODUCTION TO PROCESS CONTROL: A controller generates the control signal based on the control strategy employed and the input variable. The input variable to a controller is the error i.e. difference between the

There are various types of process control strategies such as:

- Feed back control
- Feed forward Controller
- Cascade Controller
- Adaptive Controller
- IMC based Controller
- Robust Controller etc.

In all above techniques the Feedback controller is the oldest. The combinations of the above said controllers are also employed to enhance the performance of the overall control system. Like,

Feedforward controller, feedback controller, cascade controller are usually employed cumulatively so as to reject disturbance and control the process variable effectively.

Feedback controllers have different types, which are as follows,

(a) On – Off Controller

(b) Proportional Controller

(c) Proportional Integral Controller

(d) Proportional Integral Derivative controller

These all controllers have a reference input and output measurement in form of FEEDBACK making these under the heading of closed loop control strategy. A closed loop control strategy takes reference input or the set point and the output value, which is to be controlled, as the feedback. The controlling action is then generated according to the specified controller algorithm depending upon the error which is set point minus feedback signal.

5.3.1 ON – OFF Controller:

In this type of controller the control signal sent to the actuator is either 0% or 100% e.g. in the water tank level control let there be two valves controlling the outflow and the inflow, suppose valve1(V1for the inflow) is chosen for the controlling purpose . A motor is employed as the actuator which opens or closes the valve according to current supplied to it.

Now suppose set point is lesser than the current output level then the inflow valve should be open i.e. controlling signal applied to the motor must 20 be mA according to the standards. Due to the 20mA current the motorized valve gets fully open. And the level in the tank rises up to the point where the level becomes greater than the set point. In off mode the control signal is 4mA.

The control strategy can be defined as

SET POINT > FEEDBACK → CONTROLLER OUTPUT = 100%

SET POINT <=FEEDBACK → CONTROLLER OUTPUT = 0%

The ON- OFF controller results in the continuous on off of the controller, and thus producing the oscillations in the output. That's why this controller is not used in the sophisticated environment. It is used generally in the heater temperature control system or the oven temp. Control system.

5.3.2 Proportional Controller:

In this type of controller the control signal is proportional to the error signal . For example let the error be denoted as 'e' and controller output is denoted by 'c ' , then the controller output can be calculated as

$$c = K_p \, . \, e \qquad - \ (5.18)$$

Where, ' K_p ' is the proportional constant.

This type of the controllers generates the offset error in the output i.e. a steady state error is generated in the output.

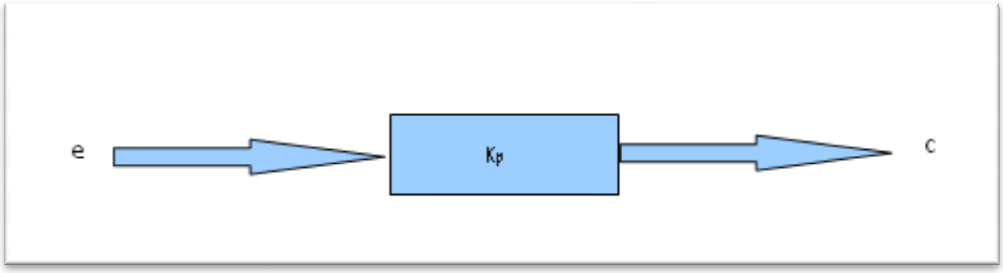

Fig 5.1 Block Diagram of Proportional Controller

5.3.3 Proportional plus integral Controller:

To remove the steady state error the integral of the error is taken and added to the proportional control action.

The controller output can be written as:

$$c = K_p \, . \, e + K_i \int e \, dt \qquad - (5.19)$$

This type of controller improves the steady state error but doesn't affect the transient response.

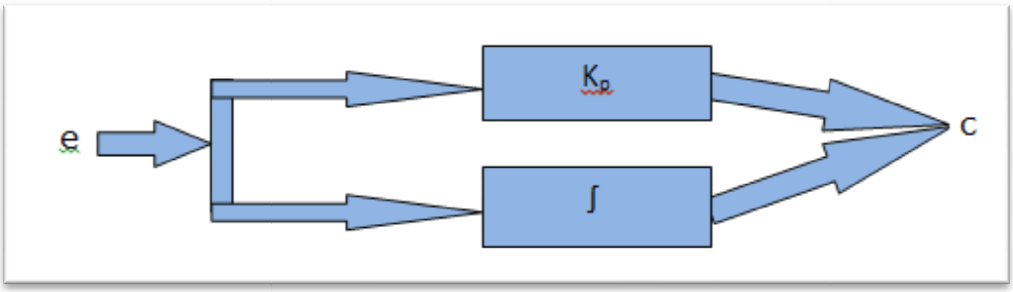

Fig. 5.2 Block Diagram of PI Controller

5.3.4 Proportional plus Integral plus Derivative Controller:

This type of controller generates a control signal which is proportional + integral + derivative of the error. The added term corresponds to the derivative of the error which improves the transient response of the system.

The control action can be formulated as

$$c = K_p \, . e + K_i \int e \, dt + K_d \frac{de}{dt} \qquad -(5.20)$$

This controller has the advantage of all the three types of the corrective actions.

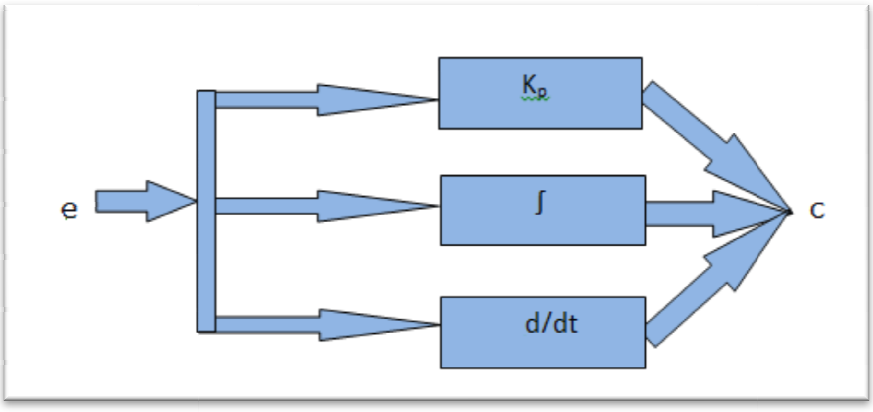

Fig. 5.3 Block Diagram of PID Controller

5.4 CONTROLLER DESIGN FOR THE DISTILLATION COLUMN:

In the present dissertation the model for the distillation column is developed on the basis of the physical laws and equations given by the William L. Luyben [9]. Section 5.2 has described the equation involved in the modeling for the column. The control scheme for controlling the composition of the products is then has been decided on the basis of these equations.

Two controllers controlling the liquid holdup in the column base and reflux drum are also employed. The feed rate F and the composition Z are given and are taken as the disturbances for the plant. Now to examine the degree of freedom of the system,[9]

5.4.1 Number of Variables:

Name of Variables	No.
Tray composition (x_n and y_n)	$2N_T$
Tray liquid flows (L_n)	N_T
Tray Liquid holdups (M_n)	N_T
Reflux Drum composition (x_D)	1
Reflux Drum flows (L & D)	2
Reflux Drum Holdup (M_D)	1
Base Composition (x_B & y_B)	2
Base Flows (V and B)	2
Base Holdup (M_B)	1
TOTAL	**$4N_T + 9$**

Table 5.1 No. of Variables in Distillation Column Modeling

5.4.2 Number of Equations:

Name of Variables	No.
Tray component continuity	N_T
Tray total continuity	N_T
Equilibrium (Trays plus Base)	N_T +1
Hydraulic	N_T
Level Controllers	2
Reflux Drum component continuity	1
Reflux Drum total continuity	1
Base component continuity	1
Base total continuity	1
TOTAL	**$4N_T$ + 7**

Table 5.2 No. of Equations in Distillation Column Modeling

Therefore the system is underspecified by two equations. This means that there are only **two** variables that can be controlled (can be fixed/manipulated). The two variables that must somehow be specified are reflux flow Rate L and vapor boilup rate V (or heat input to the reboiler). They can be held constant (an openloop system) or then can be changed by two controllers to try to hold some other two variables constant. In the present dissertation the two controllers which manipulate these variables are decoupled PID controllers, which are used to control the composition of the top and the bottom products.

5.5 MODEL PARAMETERS AND NOMINAL OPERATING POINT: The values of the model parameters used in this dissertation are as follows, [4]

_

Parameter	Value
No of trays	20
Feed tray	10
Relative volatility	1. 5
Feed composition, mole fraction (z_f)	0.55
Feed condition	Saturated liquid
Feed flow rate, Kmol/min	1
Distillate composition, mole fraction	0.96
Bottom product composition, mole fraction	0.04
Reflux rate, Kmol/min	2.7063
Boil up rate, Kmol/min	3.2063
Liquid holdup in condenser	0.50
Liquid holdup in the reboiler	0.50

Table 5.3 Distillation Column Model Parameters

5.6 CONCLUSION: An extensive discussion on the equations governing the distillation column behavior has been discussed and a base for the modeling of the system in LabVIEW has been built.

CHAPTER VI

Distillation Column Modeling & Control using LabVIEW

6.1 INTRODUCTION: In this dissertation modeling has been done in LabVIEW software. LabVIEW has a dedicated software which only deals with the Control Design and Simulations of the different plant models and control system. This part of LabVIEW is very similar to the SIMULINK of the MATLAB by MathWorks Inc. SIMULINK contains different toolboxes which deals with simulations of the different system such as Hydraulic Systems, Electrical Systems etc. LabVIEW also has different toolboxes which include PID Toolbox, Fuzzy control Toolbox, and different toolbox which deals with simulations of the plant such as Linear Systems, Non linear System, Simulation Loop etc.

This chapter discusses how the different equations depicting the behavior of the distillation column, and how the controller for distillation column have been designed in the LabVIEW.

6.2 PROGRAMMING IN LABVIEW/Block Diagram: This section has a detailed explanation of how the programming has been done to simulate the distillation column and how the controller has been employed.

6.2.1 Implementation of the model in LabVIEW: This distillation column model has been divided in six (6) parts. To simulate the model, each has been arranged and interconnected in a specified manner according to the differential equations, as the outputs of many equations serve as the input to some other equations. Different parts/subsystems and their block diagram programming, are as following,

6.2.2 Subsystem: A subsystem is a compact representation of a block diagram programming. The whole programming is under the mask and only the input and output terminal are accessible in the main window. A subsystem is in itself a complete program and act according to the program. It has its own front panel in which user can verify the output, whether it is according to specifications or not. The subsystem approach can be compared to the user defined function of the high languages like C, C++, or Visual Basic etc. the subsystem approach is very helpful

when a repetitive function has to be done. The model for the distillation column has different trays and each tray has same differential equation, except Feed tray, top tray, and Bottom Tray, with different values of the input and the output, so a dedicated subsystem for evaluating the differential equation has been employed here for the programming.

1. **Nth tray:** The equation of the nth tray has two inputs i.e. x_{n+1} and x_{n-1} and one output i.e. x_n. In addition to that a vapour liquid equilibrium has also been used to calculate the value of y_n. This value of y_n is being used to solve equation further. The equation for the nth Tray is as under,

$$\frac{d(M_n x_n)}{dt} = L_{n+1}\, x_{n+1} - L_n\, x_n + V y_{n-1} - V y_n \qquad -(5.11)$$

The subsystem for the nth tray is shown below,

Fig 6.1 Subsystem for nth Tray

Block diagram for the subsystem of nth tray has been shown in following fig.,

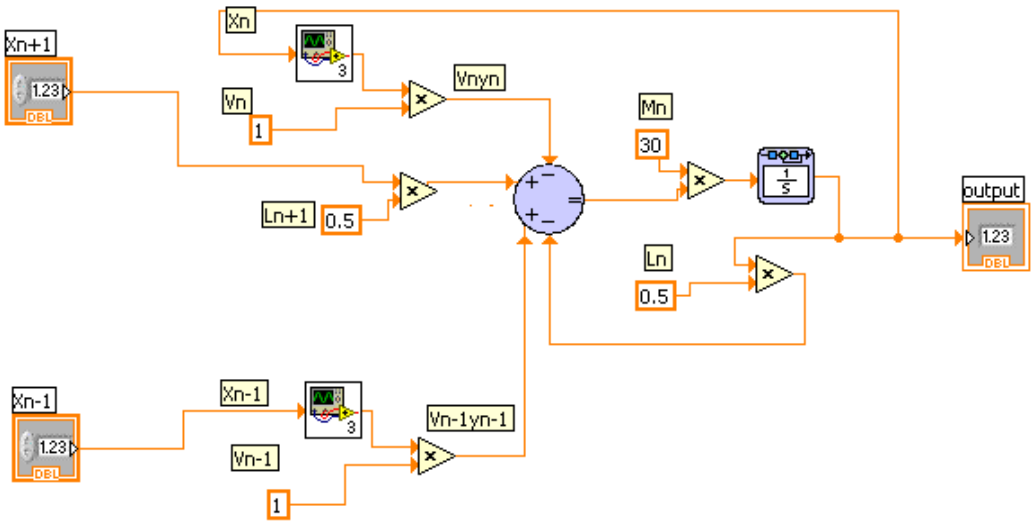

Fig 6.2 Block Diagram for nth Tray

2. **Feed Tray:** The equation of the Feed tray has four inputs i.e. x_{n+1} , x_{n-1}, x_f and z_f and one output i.e. x_{NF}. In addition to that a vapour liquid equilibrium has also been used to calculate the value of y_{NF}. This value of $y_{NF}$is being used to solve equation further. The equation for the Feed Tray is as under,

$$\frac{d(M_{NF}x_{NF})}{dt} = L_{NF+1}\,x_{NF+1} - L_{NF}\,x_{NF} + Vy_{NF-1} - Vy_{NF} + z_f \quad -(5.13)$$

The subsystem for the Feed tray is shown below,

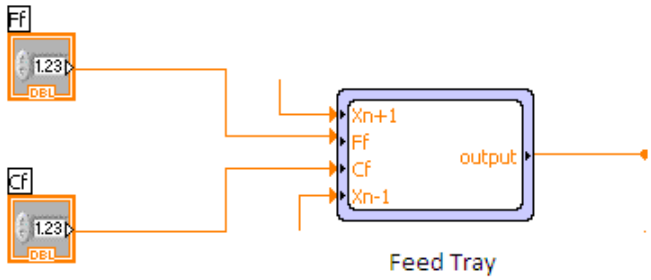

Fig 6.3 Subsystem for Feed Tray

Block diagram for the subsystem of Feed Tray has been shown in following fig.,

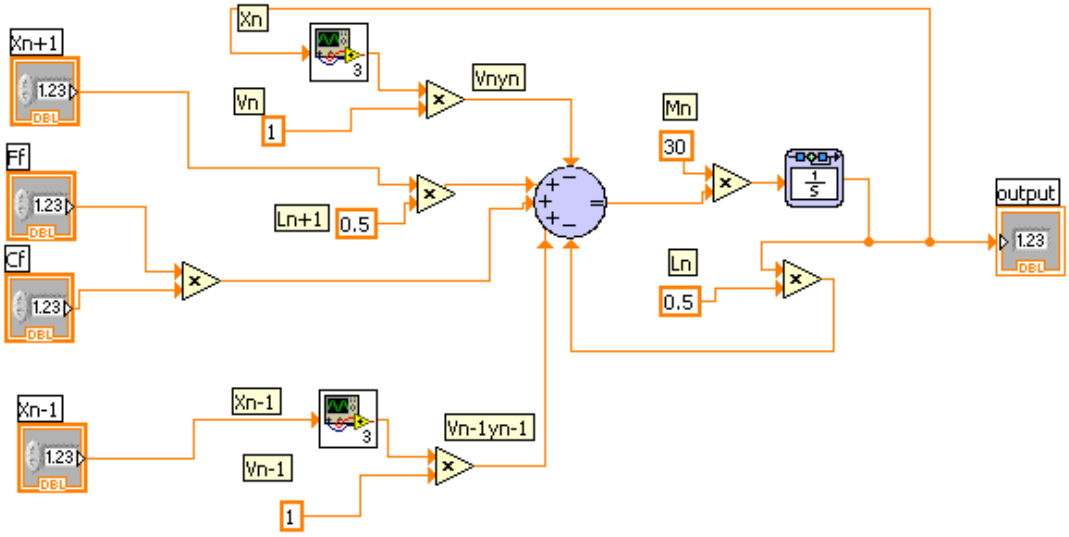

Fig 6.4 Block Diagram for Feed Tray

3. **Vapor - Liquid Equilibrium:** A vapor liquid equilibrium has been used to predict the value of the liquid and the vapor amount on the trays. The subsystem and equation related to vapor liquid equilibrium is shown as under,

$$y_n = \frac{\alpha x_n}{1 + (\alpha - 1)x_n} \qquad -(5.1)$$

Fig.6.5 Subsystem for Vapor liquid equilibrium

Block diagram for the subsystem of Vapor Liquid Equilibrium has been shown in following fig.,

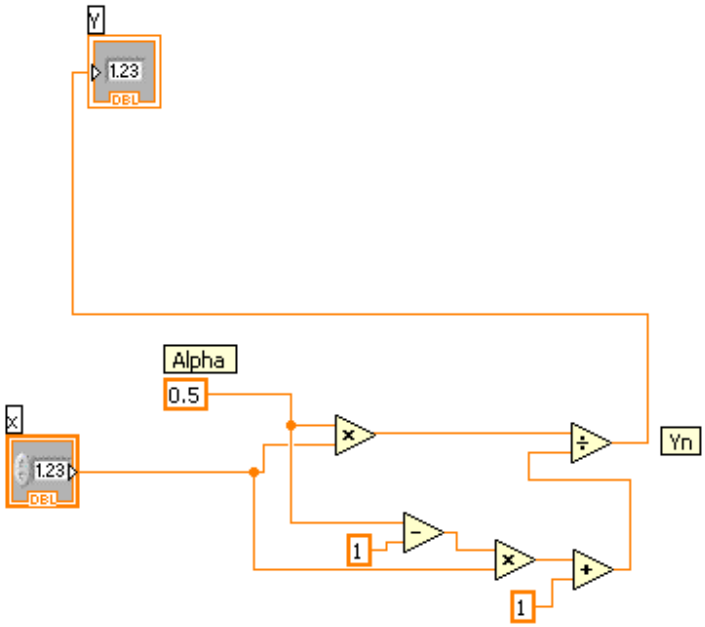

Fig. 6.6 Block Diagram for the Vapor Liquid Equilibrium

4. **Condenser and Reflux Drum:** The differential Equations related to the Condenser and reflux drum are as follows,

$$\frac{d(M_D x_D)}{dt} = Vy_{NT} - (L + D)x_D \qquad -(5.5)$$

The equation for the condenser and reflux drum are not iterative, hence is not made as subsystem and are used directly in the block diagram, as under,

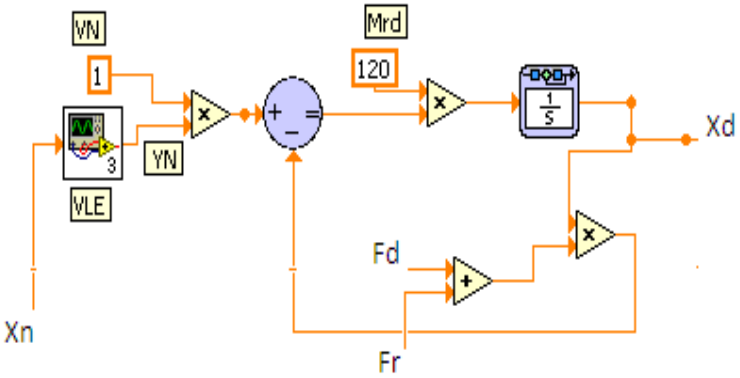

Fig. 6.7 Block Diagram for Reflux Drum

5. **Top Tray:** Top tray is the upper most tray in the distillation column and its differential equation is somewhat different from other trays, as the part of the distillate is fed back to the top tray. This feedback is known as Reflux. The equation for the tray is ,

$$\frac{d(M_{NT} x_{NT})}{dt} = Lx_D - L_{NT}\, x_{NT} + Vy_{NT-1} - Vy_{NT} \qquad -(5.7)$$

The block diagram programming is as under,

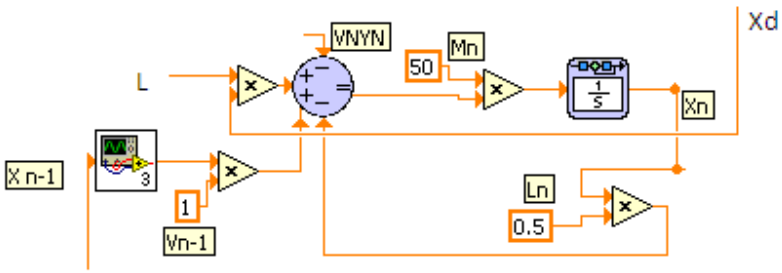

Fig. 6.8 Block Diagram for Top Tray

6. **Column Base:** The equation for the column base and Reboiler is as under,

$$\frac{d(M_B x_B)}{dt} = L_1 x_1 - V y_b - B x_B \qquad -(5.17)$$

The block Diagram for the column Base and Reboiler is shown in fig. ,

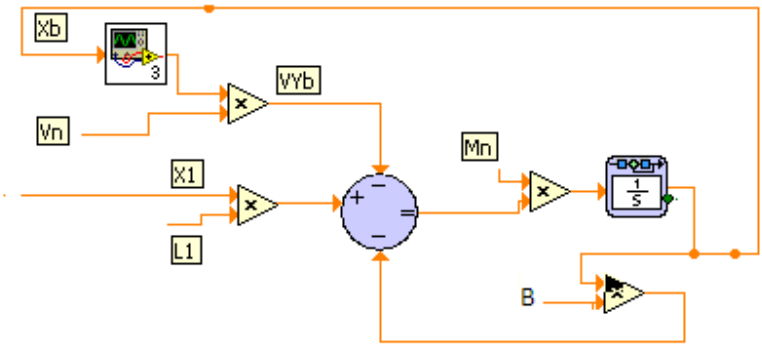

Fig. 6.9 Block Diagram for Column Base and Reboiler

On arranging these different block diagrams, a complete model for the ideal binary distillation column has been built. Different trays have been arranged, such that the output of one serves as input to other, in order to satisfy the differential equations.

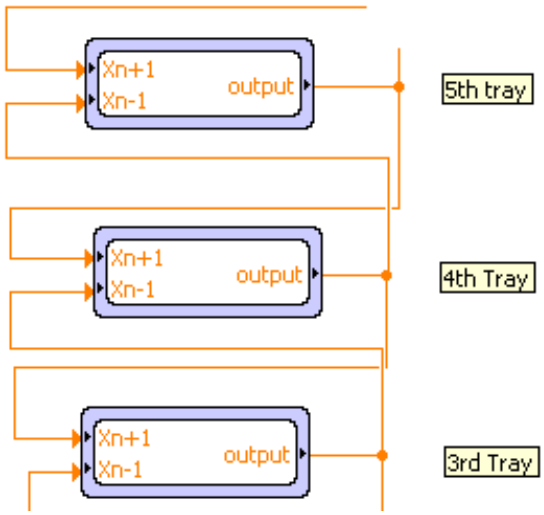

Fig. 6.10 Interconnection of different trays

6.3 FRONT PANEL: Front Panel is the space where the distillate and the bottom composition monitoring and values for the different parameters of the controller can be varied by the user. Front panel for the above described Programming is shown in Fig. 6.11,

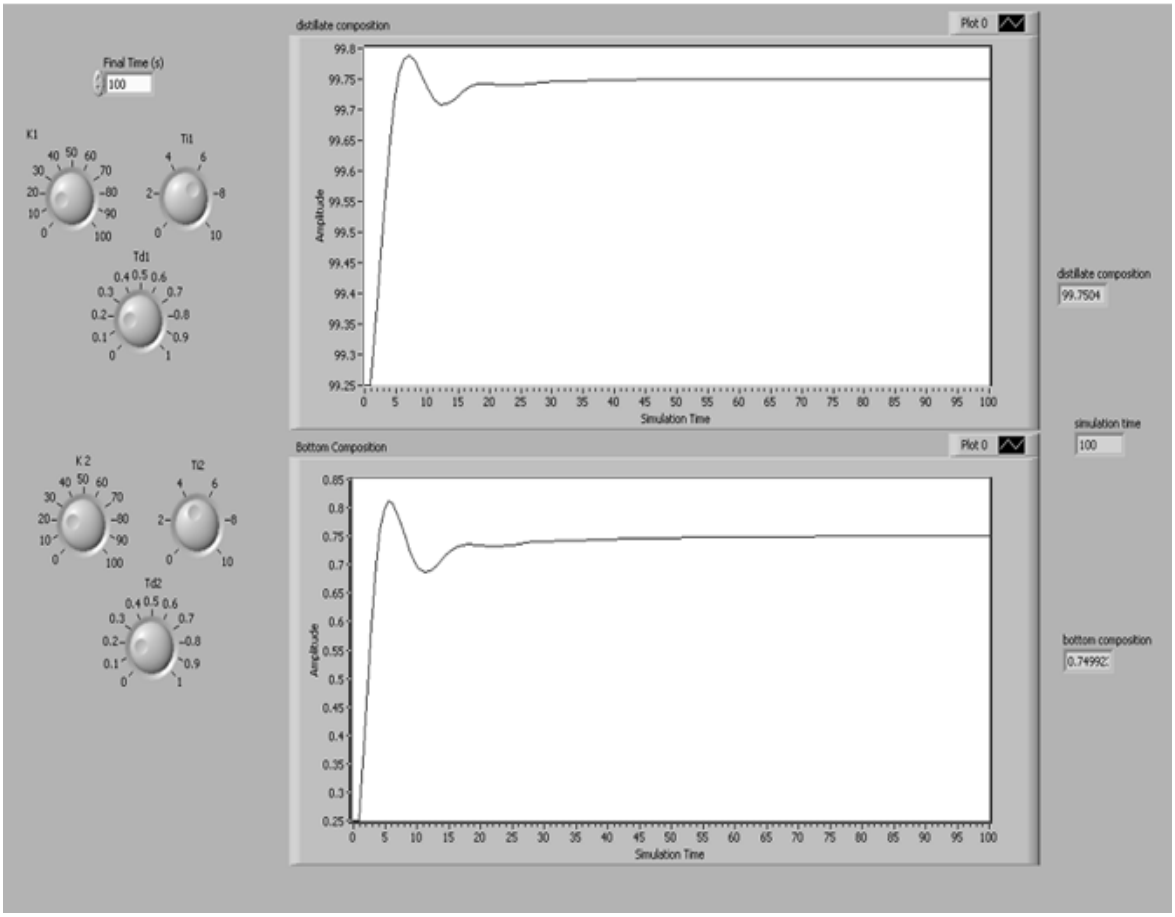

Fig. 6.11 Front Panel of Distillation Column Model

6.4 CONCLUSION: Implementation of the distillation column model through different available icons in LabVIEW library has been presented in the chapter.

CHAPTER VII

Results and Discussion

The model for Distillation Column is linearized around the point [99.25%, .25%] i.e. the distillate composition and the bottom product composition respectively. A step change of magnitude [.5 %] in the composition has been fed to the system and the variation in the composition of the top and the bottom product has been analyzed. Different combinations of the values for K_p, T_I, T_D has been used to observe the variation of the composition of the products.

7.1 LIST OF CONTROL STRATEGIES AND THEIR PARAMETERS' VALUES:

CASE	CONTROL STRATEGY	PARAMETERS' VALUES					
		Controller 1			Controller 2		
		K_{p1}	T_{i1}	T_{d1}	K_{p2}	T_{i2}	T_{d2}
Case I	P Control	49.095	-	-	32.183	-	-
Case II	PI Control	24.7486	9.24609	-	28.1027	7.3494	-
Case III	PI Control	16.9575	2.9749	-	24.6525	2.4616	-
Case IV	PID Control	68.937	6.28185	.3295	29.605	4.928	.1169
Case V	PID Control	15.3594	6.54891	.1891	21.848	4.363	.1857

Table 7.1 List of Parameters for different Controllers

Case 1: *Simple Proportional Controller:*

K_{P1} = 49.095

K_{P2} = 32.183

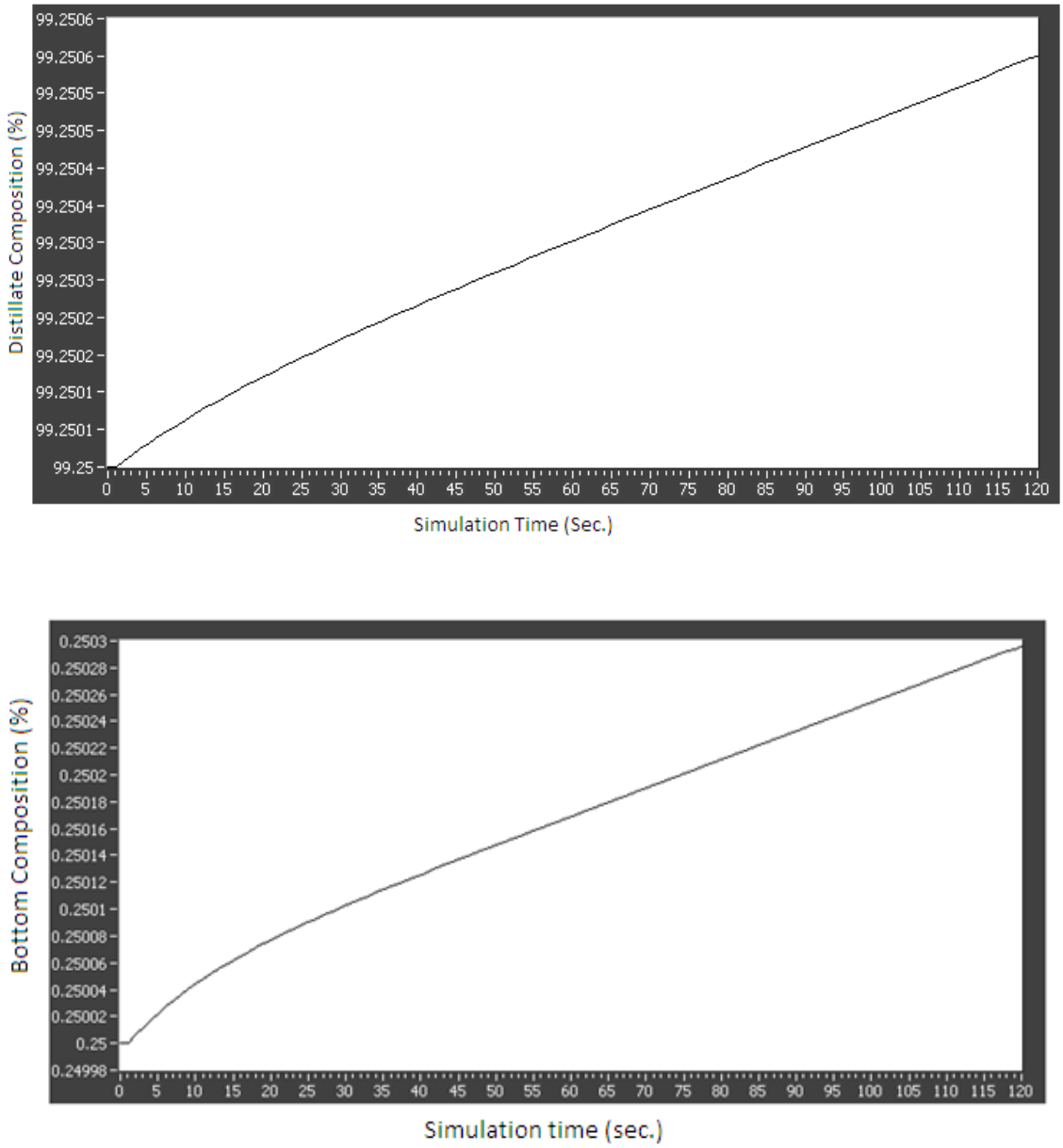

Fig. 7.1 Variation of Distillate & Bottom Composition v/s Time (P Control)

Case 2: *Proportional Integral Control:*

$K_{P1} = 24.7486$ $T_{i\,1} = 9.24609$

$K_{P2} = 28.1027$ $T_{i\,2} = 7.3494$

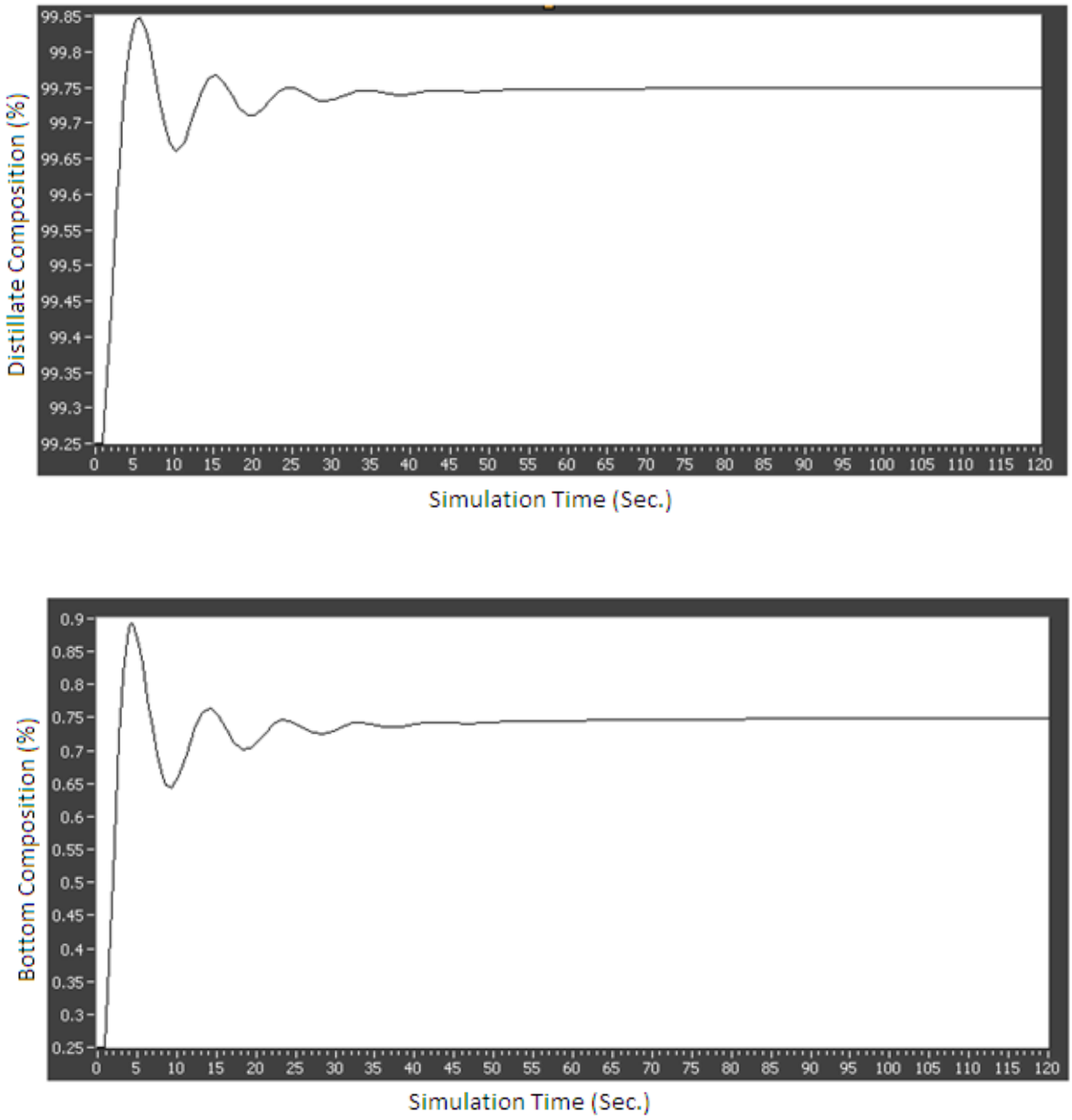

Fig. 7.2 Variation of Distillate & Bottom Composition v/s Time (PI Control)

Case 3: *Proportional Integral Control:*

$K_{P1} = 16.9575$ $T_{i\,1} = 2.9749$

$K_{P2} = 24.6525$ $T_{i\,2} = 2.4616$

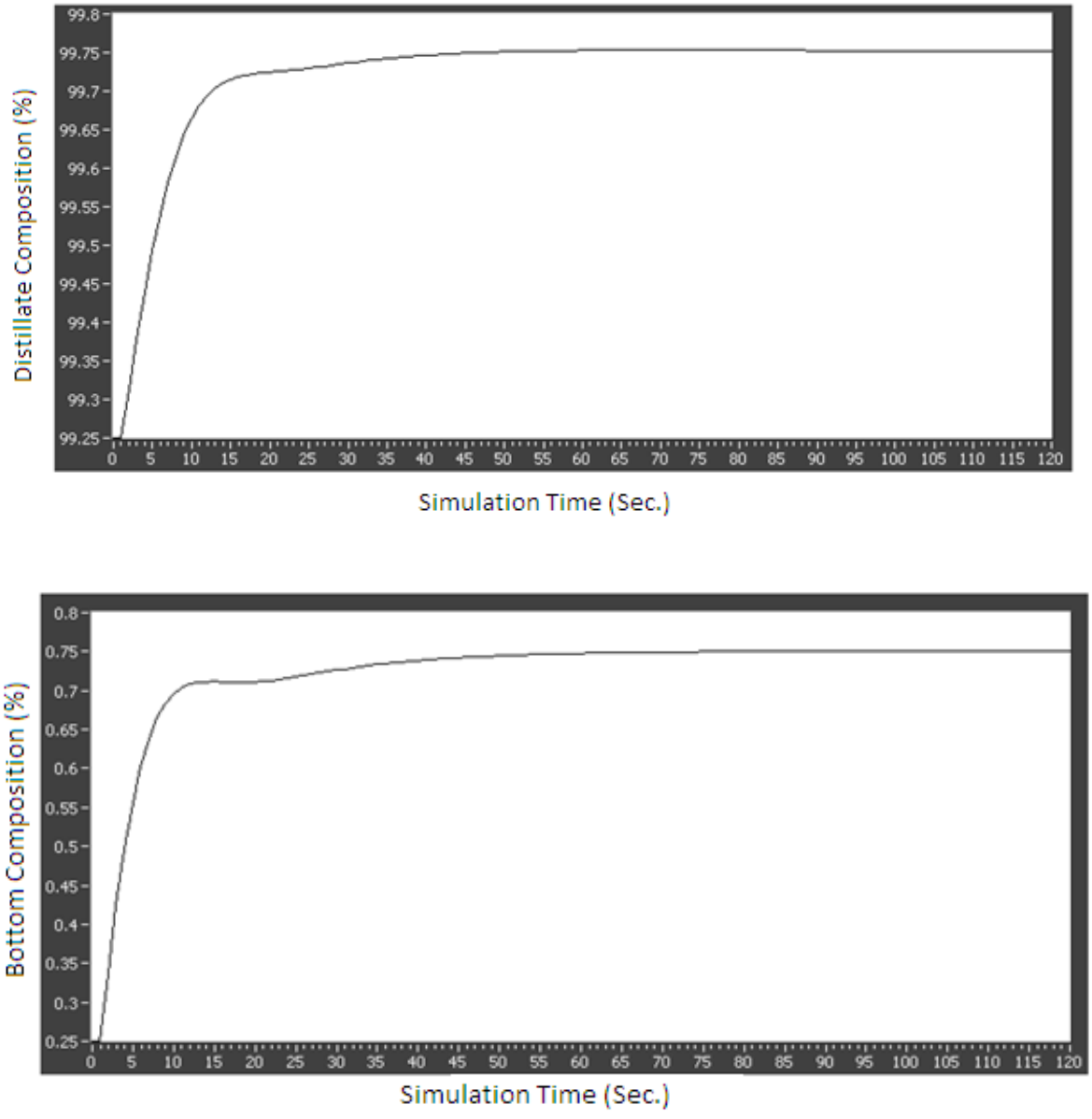

Fig. 7.3 Variation of Distillate & Bottom Composition v/s Time (PI Control)

Case 4: *Proportional Integral Derivative Control:*

$K_{P1} = 68.937$ $T_{i\,1} = 6.28185$ $T_{d\,1} = .3295$

$K_{P2} = 29.605$ $T_{i\,2} = 4.928$ $T_{d\,1} = .1169$

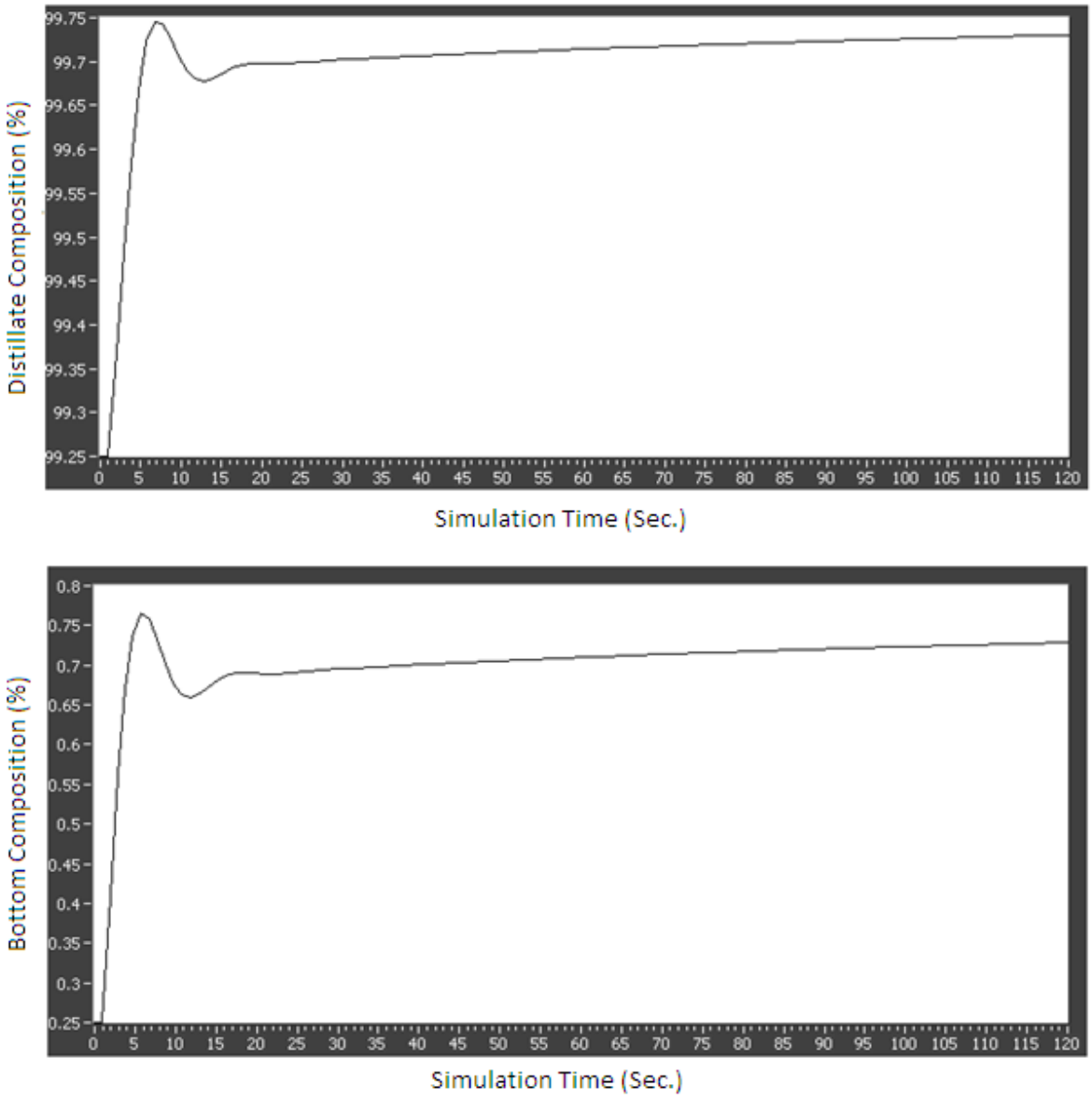

Fig. 7.4 Variation of Distillate & Bottom Composition v/s Time (PID Control)

Case 5: *Proportional Integral Derivative Control:*

K_{P1} = 15.3594 $T_{i\,1}$ = 6.54891 $T_{d\,1}$ = .1891

K_{P2} = 21.848 $T_{i\,2}$ = 4.363 $T_{d\,1}$ = .1857

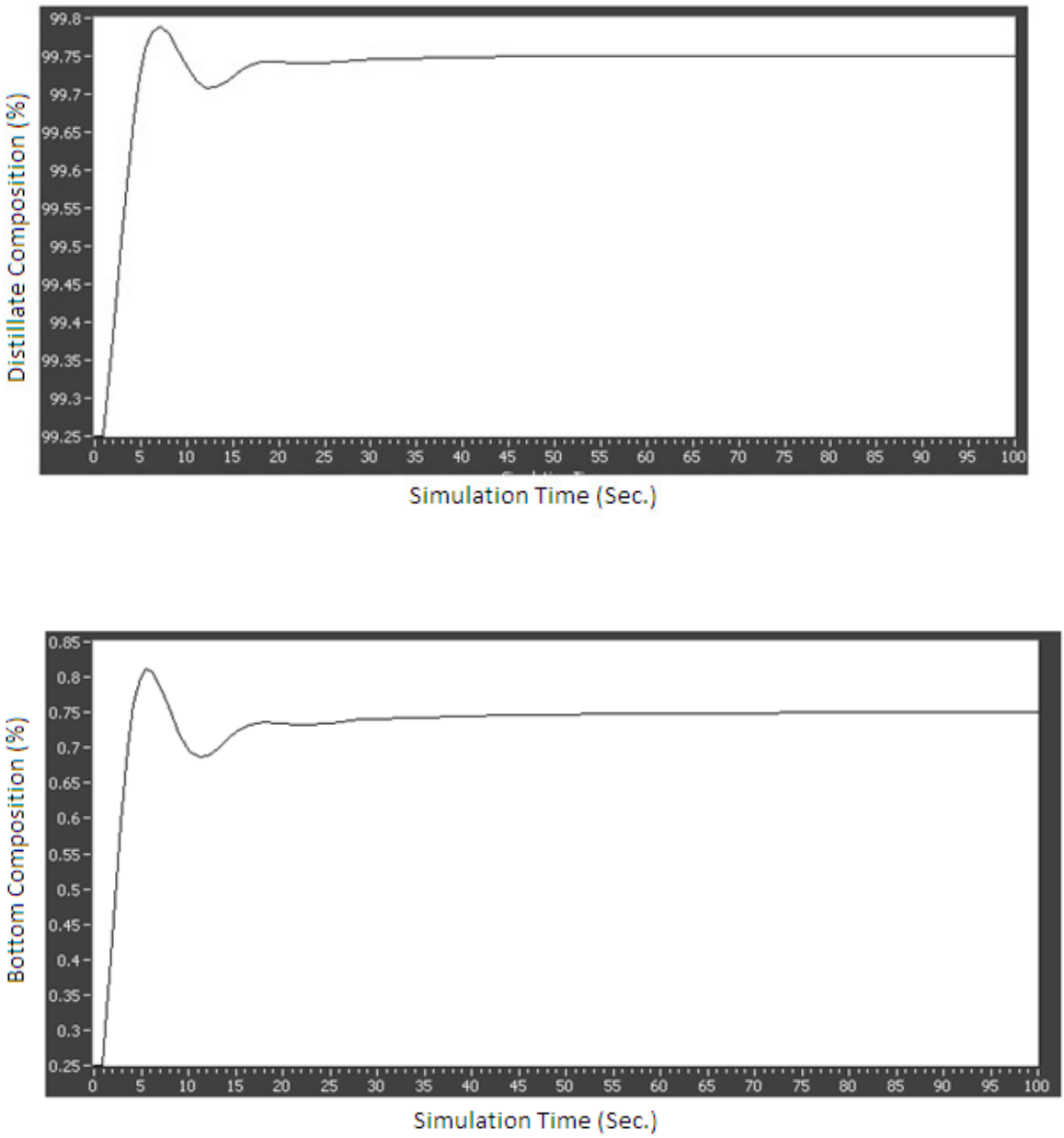

Fig. 7.5 Variation of Distillate & Bottom Composition v/s Time (PID Control)

7.2 DISCUSSION ON RESULTS: Various parameters which depict the performance of the control strategy applied to the model are summarized in the following table.

SUMMARY OF THE RESULTS:

CASE	Max. Overshoot (%)	Settling Time	Steady state Error	Desired Response Achieved?
Case I	NA	Very Large	Very Large	NO
Case II	1%	37 sec.	Negligible	NO
Case III	No overshoot	51 sec.	Negligible	NO
Case IV	.04%	80 sec	Large	NO
Case V	**.03%**	**26.4 sec**	**Negligible**	**YES**

Table 7.2 List of Different parameters depicting performance

Case I: In this strategy only proportional controller is applied and the Steady state error found to be very large, thus the controller was not acceptable.

Case II: In this a PI controller is employed, although steady state error came down as integral controller has been added, but the Settling time and overshoot are still not acceptable, thus the PI controller with the said values of parameters is not acceptable.

Case III: In this strategy also a PI Controller is employed with different values of the parameters. This case does not any overshoot but the Settling Time has been increased to 51 sec. Though the Controller has brought down the steady state error to a permissible limit but due to increased value of the setting time the controller is not acceptable.

Case IV: Derivative Controller has been introduced along with the PI Controller used in the Case 2 and 3. In this case, although the overshoot has been reduced significantly, but due to poor tuning of the parameters of the controller, the response is not desirable.

Case V: In this case, PID controller with tight tuning of the parameters is used. Steady state error has been removed by application of the integral controller and the transient response has been improved with the application of the derivative controller. The overshoot has been reduced to a

value of .03% and the settling time is also reduced to the value of 26.4 sec, and the strategy is found most suitable.

7.3 FUTURE SCOPE OF THE WORK:

In this dissertation a mathematical model and a suitable control strategy has been applied. The mathematical model in the present work is based on the molar concentrations of the components in the product streams and according to them a controller has been employed. The present work can be further explored in areas, such as, instead of the molar concentrations, the mass flows can be used to develop a model for the column and hence a controller to make the distillation process energy efficient and effective. More advanced controllers such as robust controller, Fuzzy Controller, and Neural Controller can also be studied for their feasibility to be employed with distillation column dynamics.

Moreover, the present work can be extended to a real distillation column and the process variables can be fed to the LabVIEW with the aid of a Data Acquisition card. The Process variables can be the temperature of the trays, outputs of the chromatographs which can infer the composition of the components in the product stream. Consequently the manipulated variables according to the control strategy employed can be varied in order to keep the composition of the components of desired value.

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