COMPARATIVE STUDY OF RELIABILITIES OF DIVIDED WALL DISTILLATION COLUMN AND PETLYUK COLUMN

A DISSERTATION

Submitted in the partial fulfillment of the

requirements for the award of the degree

of

MASTER OF TECHNOLOGY

in

CHEMICAL ENGINEERING

(With Specialization in industrial Safety and Hazard Management)

By

KOUSHALENDRA KUMAR

DEPARTMENT OF CHEMICAL ENGINEERING

INDAIN INSTITUTE OF TECHNOLOGY, ROORKEE

ROORKEE-247667, Uttarakhand, (INDIA)

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CANDIDATE’S DECLARATION

I hereby declare that the work which is being presented by me in this evaluation report entitled “**Comparative study of the reliability of divided wall distillation column and the petlyuk column”,** submitted in partial fulfillment of the requirement for the award of the degree of, “**Master of Technology in Chemical Engineering**” with specialization in “**Industrial safety and hazard management**”, and submitted to the Department of Chemical Engineering, Indian Institute of Technology, Roorkee, is an authentic record of the work carried out by me during the period July 2012 to June 2013, under the guidance of Dr. VINEET KUMAR**,** Associate professor, Department of Chemical Engineering, Indian institute of Technology, Roorkee.

Date:

Place: IIT, Roorkee

(KOUSHALENDRA KUMAR)

CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

Dr. VINEET KUMAR
Associate Professor,
Department of Chemical Engineering
Indian Institute of Technology, Roorkee

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Koushalendra Kumar

Enrolment No. 11516006

M.Tech (ISHM.) 2nd year

IIT Roorkee

ABSTRACT

The development in the field of the distillation technology is continued from a long past for the better structure and better column design. This reduces the outer complexity of the system, capital cost, and improves energy efficiency. The Petlyuk column and the divided wall distillation column is such advancement in this field where cost and energy are saved a lot. A reliability study of any system is important as well because it gives an idea that how long the system survive in the working environment. Failure of a system depends on failure of various components of the system and several other factors. If we have a clear idea about the nature of failure, we can easily predict the longevity of the system.

Current work is focused on comparing trouble free operational time of a Petlyuk arrangement of two distillation columns vis-à-vis a divided wall distillation column. Different component of the Petlyuk column and the divided wall distillation column, whose probability of failure during the operation is possible, is enlisted and their failure rate assembled through the reliability handbook. Comparison between these two systems gives a picture regarding the better reliable system. It will enhance the chances of application of these columns in various fields with ease and efficient way. This also gives a view about the safety system to be kept in case of the failure of the system. A well protected system last long and save the precious life as well.

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NOMENCLATURE

$R(t)$	Reliability Function
$H(t)$	Cumulative Hazard Function
$f\ (t)$	Probability Density Function
$z\ (t)$	Instantaneous Failure Rate
$n_s(t)$	Number of Component Survived
$n_f(t)$	Number of component Failed
λ	Failure Rate

Abbreviations

MTTF	Mean Time To Failure
CFR	Constant Failure rate
DFR	Decreasing Failure Rate
IFR	Increasing Failure rate
DWC	Divided Wall Distillation Column

CHAPTER-1 INTRODUCTION

We are moving ahead with the empowering our society in all field of development i.e. social, economical and the industrial front. As the time goes by, we have added responsibility to serve our society better and more innovative way. From the pass to till now every day we are contributing new to our development vis-a-vis to create an innovative and new technically strong and sound system to minimize the energy and cost effect to fulfill the added requirement of the ever increasing population. But this added benefit become bane when it brings disaster. So a prevailing question ahead to us is how we minimize this disaster. It may be possible through by creating a sound safety system to safeguard our added benefit. So providing a good safety system becomes a necessity of our modern industry. A system can only be placed once we well familiar with the failure analysis of the system i.e. how system fails. By analyzing different failure rate of the system we can predict its longevity and its operating and other cost to replace it.

Reliability study is one of the ways to find life of the operating system. It is a time based quantitative analysis tool of the working system which provides the clue about the operating life of the system. Among all the systems being used in process industry, the distillation system is most energy intensive. It is a complex system consists of several smaller units. This system is also prone to the frequent failure, so a systematic analysis of this system, its chances of failure and its operating condition will give picture to safeguard the system from the various possibilities of the failure. Distillation is most important method used in the chemical industry and the appropriate integration of the distillation column with overall process will save sufficient energy. There are several arrangements for the distillation column for winch the cost of operation and the energy requirements are different. As the time passes new innovation brings new technical expertise in this area. This current work is also concentrate toward the bringing an analysis of a better system by comparing their reliability.

1.1 Distillation column

“Distillation is the process of separating a mixture of component from its boiling mixture based on its volatilities. It is a physical separation process where components are separated without chemical reaction.” Mixture can be of different component, may be a binary, ternary or more. Based on its physical properties and different parameter the distillation column may be designed. As the time passes the distillation column getting renovated with new technological development and processed the mixture more efficiently and more economically. Below diagram gives a glimpse about the distillation column.

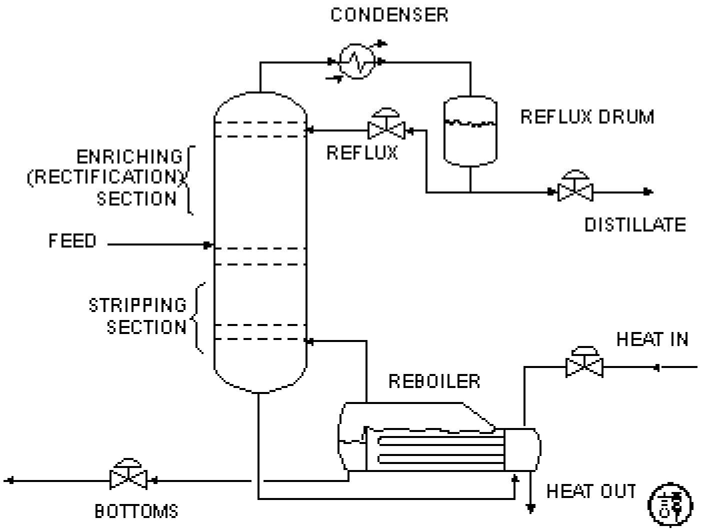


Figure-1: A simple Distillation Column

1.2 Petlyuk column:

As the number of component increases in the mixture of the liquids, it’s become very difficult to separate through a simple distillation column. New designs came up for the solution and it emphasis on the attaching a new column as the side stripper and the side rectifier. But new structures have always more energy requirement and more burdens on the pocket. Many solutions came for reduction of the energy requirement and the capital cost. Among them thermal integration was one of them. In the year 1965, Petlyuk came up with a design of a distillation column viz. fully thermally coupled distillation column.

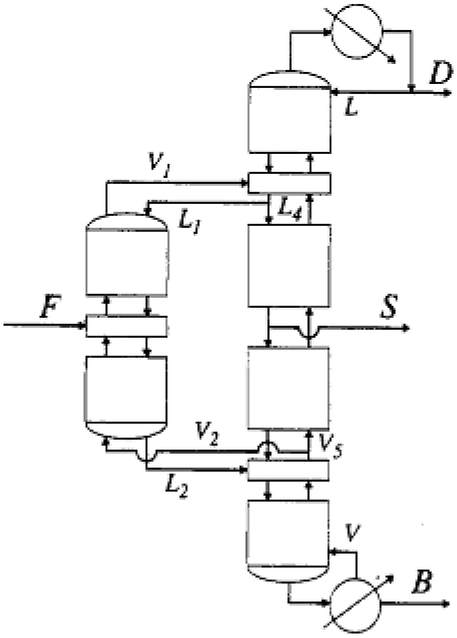


Figure-2: A simple Petlyuk Column

A two column implementation of the Petlyuk column is shown here. It has a prefractionator having reflux and the side stream from another column which has condenser and the reboiler attached to it. Petlyuk column has many more degree of freedom as compared to other column. For most separation the fully coupled distillation column has more efficiency and thermodynamically more stable than the conventional arrangement. But these all column design is very complex and need a complex control system to operate.

1.3 V- min diagram analysis:

V-min diagram is the analysis tool which can demarcate among several sharp and non sharp thermally coupled distillation columns and the conventional column boil up requirement. It can extend to the non ideal solution also and it uses the Underwood equation .it is also used for to find the flow rate for the different system. Overall minimum energy requirement is shown by the highest peak in the V-min diagram.

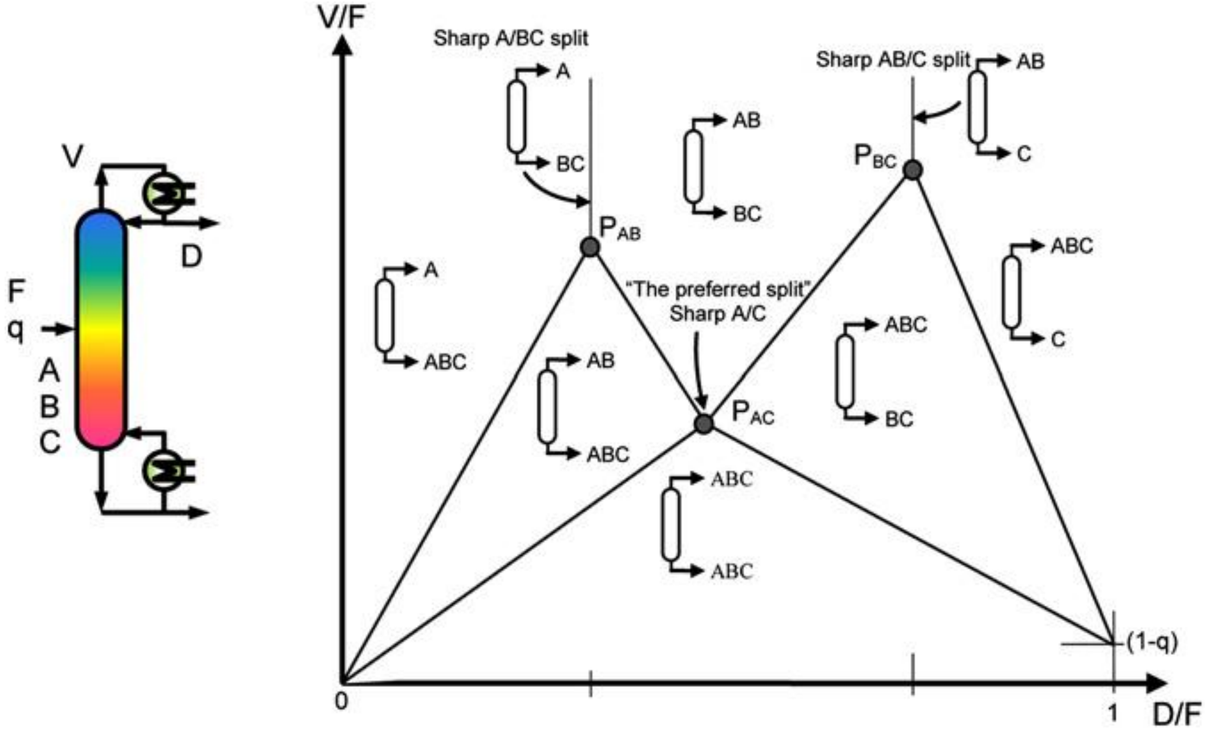


Figure-3: A V-min diagram

In this diagram, mainly the different energy requirement is shown in the different column arrangement. Minimum energy used is for the highest peak.

1.4 Divided Wall Distillation column:

Divided wall distillation column is the very innovative development in the area of the distillation column. In this concept a distillation column is separated in to two sections within which work as the two different columns. This development brought the capital cost and energy requirement to a very minimal level. Divide wall concept came very early when Wright patented (1949) for it. But the research and industrial application of it came very late. In the year 1985 first time BASF applied this concept and designed and operated divided wall distillation column.

1.5 Construction detail:

In the divided wall distillation column, the lateral mixing between the liquid and the vapor stream is prevented through the vertical partition by the application of flat metal sheet which are welded to the system or the flexible thin metal sheet which are stacked together without welding. Wall flow is always avoided since it impure the product. The stacking of the metal sheet is easier because it provide better to assembly and easy asses by the crew. In the case of welding the wall has to bear the added stress effect. The heat transfer across the wall is prevented by the application of the thermal insulation to the wall for the high purity. The thermal stress should be measured so that the high temperature does not lead to the bending of the material. Feed plates are stacked at proper height and their relative position is determined by finding the ratio between the relative volatility of the component. Mostly the position of the divide wall is in the middle but an off centered position is also possible.

Figure-4: A welding of the divided wall in to the column

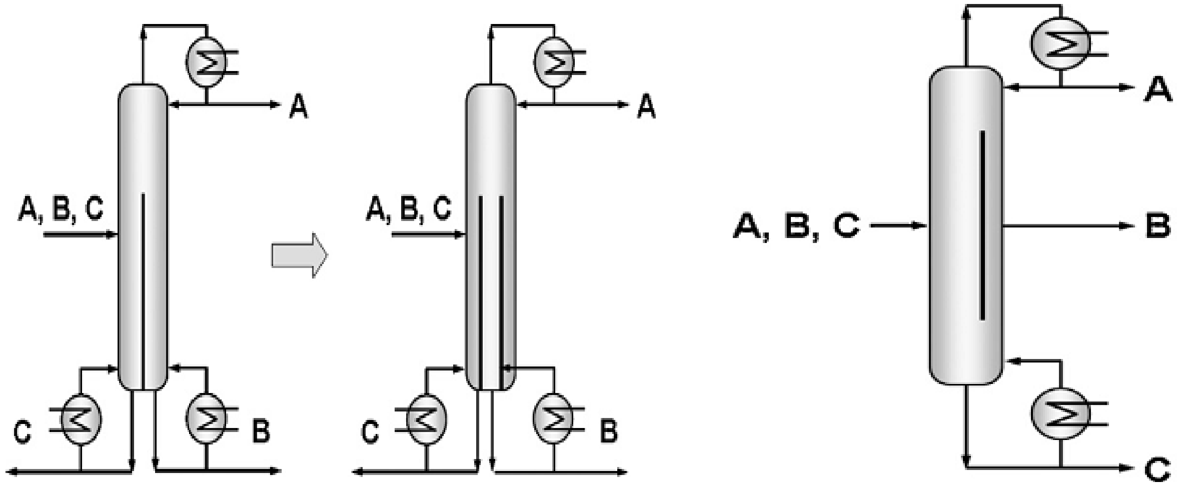


Figure-5: Position of the divided wall in the column

1.6 Designing of the DWC:

The design of the divided wall distillation column is manifold complex then the conventional column design. For the conventional design of the column four parameters are required whereas for the design of the divided wall distillation column requires eleven parameter altogether for the separation of the three components. The gas and liquid distributions are determine by the cross section and the internal of the two section of the columns since the two section of the column has equal pressure drop. Divided wall distillation column is applied at various places to get the high purity component but still it is not widely used in the industry due to several limitations. It needed much more research attention.

CHAPTER -2 LITERATURE REVIEW

Petlyuk et al. (1965): Petlyuk work mostly deals with the Distillation and intensive unit operations, and the optimal design of distillation sequences. It promises considerable savings in both capital and operating costs. The use of intricate nonstandard distillation columns, suggested by Petlyuk, have ample savings in capital costs as well as in energy spending in comparison with straight one-feed two-product distillation columns. Both the conventional and nonconventional column arrangements are used for the separation of a mixture into three different products. Complex columns are also very easy to retrofit and can be applied with a small modification. He has given the different configuration or the arrangement for the distillation of the ternary system of component. He basically designed the column having coupled along with another column and enhancing its efficiency with respect to its energy requirement. These configurations are widely used in the petroleum industry and the cryogenic distillation. They are saving up to the 30-percent capital and the energy cost.

Chavez et al. (1986): Chavez mainly worked on the Petlyuk column and did his work in the field of multiple steady states in the complex distillation column. He found that, at the steady state, a petlyuk design has a five degree of freedom and it has four solution when deals with the three component.

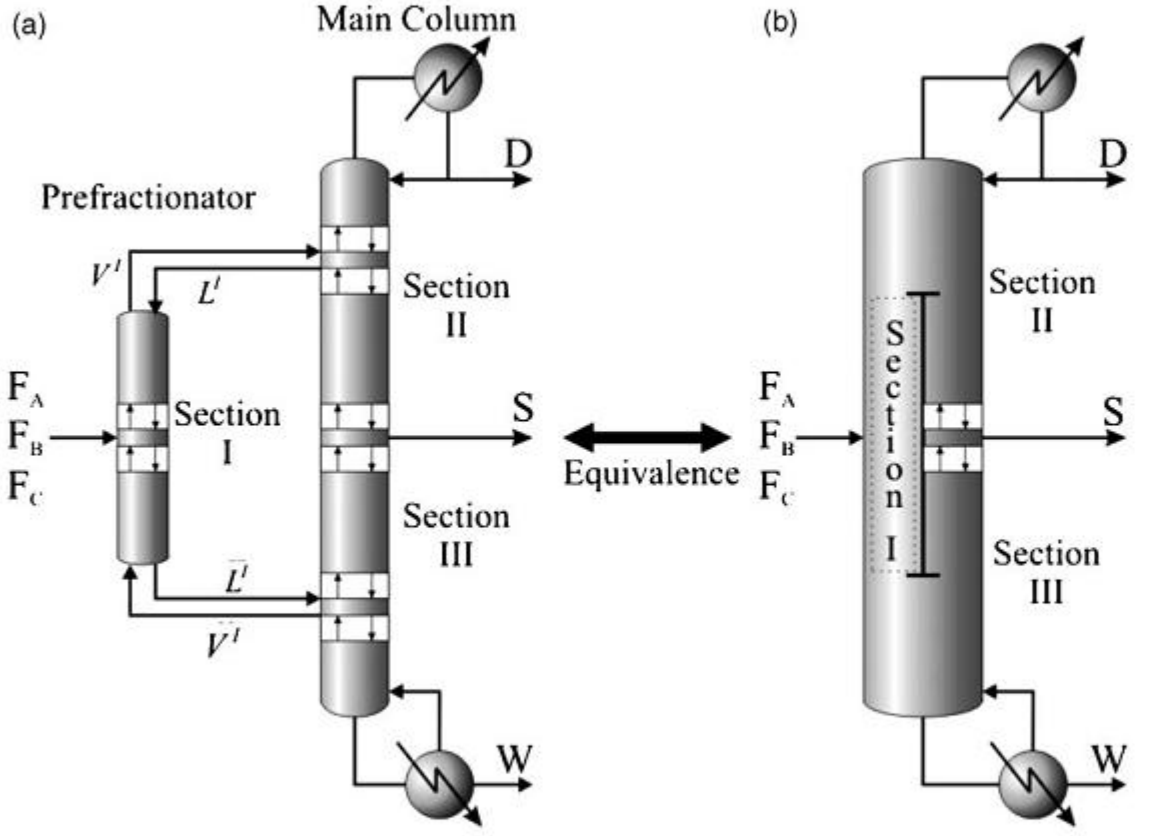
Norbert Asprion and Gerd Kaibel (2010): This paper mainly deals with the fundamentals of the divided wall distillation column and its recent development and scope in the field of the distillation column. It conveys all the technical aspect of the divided wall distillation column and its tolerance limit to the stress effect. It completely handles the construction details and the design of the divided wall distillation column. The divided wall distillation column has the broad area of application with a simple purity demand to the very high grade of purity i.e. in ppm. Recent development in the field of divided wall distillation column is very promising for four and more component. The study of controllability and operability is described in this paper.

Maria Serra et al (2000): The main objective of this paper is to see the influence of the design and operating condition in the controllability of the divided wall distillation column. It analyses, the best optimum design, for the different optimal reflux ratio to the minimum reflux ratio. Non optimal design is compared with the optimal design and the effect of controllability was studied. The two optimal design are compared i.e. the inventory control at the condenser level and the inventory control at the reboiler level. Three non optimum designs are also discussed in detail. The controllability of different operating conditions is handled along with varying the number of trays. It was found that, optimal designs have same set of preferred manipulated variable, and a non optimal design has good controllability when split variable appear.

Jose A. Caballero and Ignacio E. Grossmann (2004): His work presents the superstructure optimization for the designing of components. The work deviates from the conventional sequencing of condenser and reboiler to the thermally coupled sequencing. He used the Underwood–Fenske–Gilliland model, where he sequenced the task to be performed and then he selected best configuration among all thermodynamically equivalent configuration (intermediate configuration).It uses decomposition method. However, this paper does not deals with the divided wall distillation column but it shades a light over its future prospect where multiwall can be used instead a single wall.

A. Jimenez et al. (2003): This paper analyses the six different configuration of the Petlyuk column along with the thermally coupled distillation column. Two of them are use to interconnected with unidirectional flow while other four configurations show a reduction in the connectivity. Although Petlyuk column is superior then the conventional direct and indirect configuration but structure of the column creates an operating problem due to its bidirectional flow of the vapor stream. The entire six configurations are studied in this work and the Petlyuk column was designed and analyzed for energy consumption. It was found that, several structures have very high potential for the future for the energy efficiency. Even the new structures have improved control properties for the Petlyuk column.

Nelly Ramirez-Corona et al. (2010): the paper presents the optimization approach for the petlyuk column and divided wall distillation column. The paper also applies the short cut method for the design of such system that can be modeled as the non linear programming problem. In the paper, basically the conventional petlyuk column where a prefractionator was used is removed and a divided wall is added which use as the prefractionator.

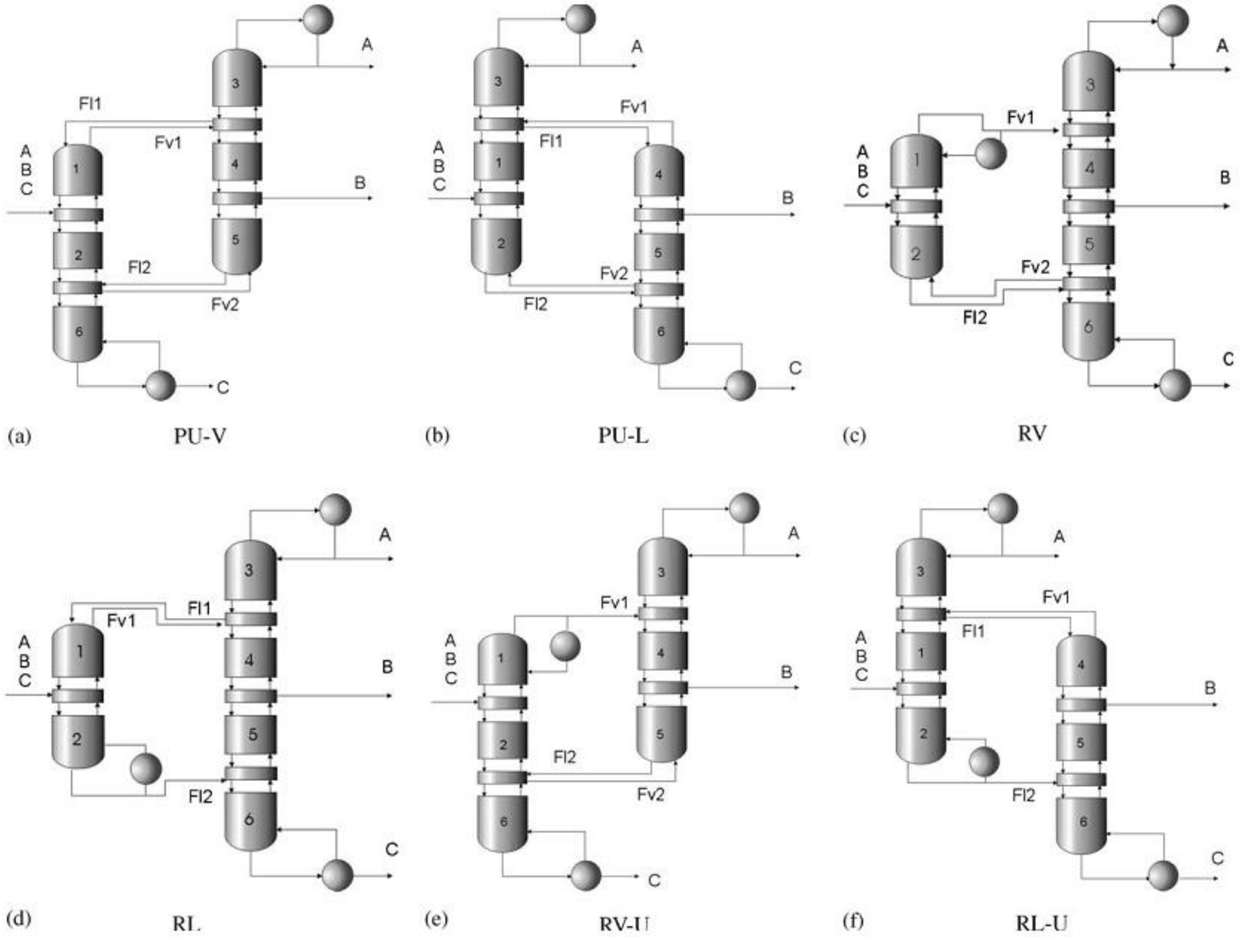


The Petlyuk system. (a) Original arrangement. (b) Implementation as a divided-wall column.

Figure-6

In this configuration, the system is divided in a three sections and for all three sections the minimum reflux ratio has been calculated and a dominant section has been found for the main column. Two systems are optimized and found the optimum condition for the minimum energy requirement.

Salvador Hernandez et al. (2006): In this paper, Salvador et al. found and compared the thermodynamically equivalent distillation schemes, which are energy efficient and they are alternative to the Petlyuk column. In this work the second law calculation was performed for the petlyuk column and other six alternative combinations that show the unidirectional flow pattern. These alternative combinations show the better operational properties then than the usual Petlyuk column. Work is a sincere effort to show the alternative scheme which is thermodynamically equivalent to the Petlyuk column and easy to implement with energy saving



(a) PU-V (b) PU-L (c) RV

(d) RL (e) RV-U (f) RL-U

Figure-7: Diagram of Different arrangement of Petlyuk Column

Source: Salvador Hernandez et al. (2006)

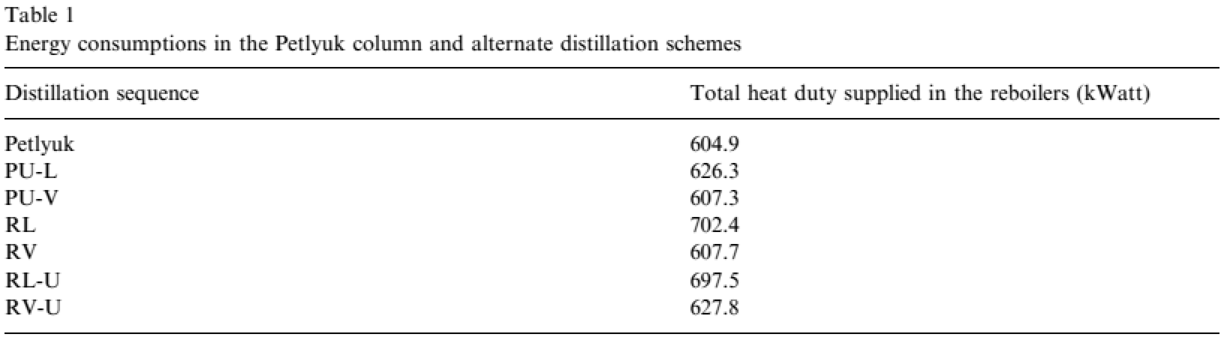


Table 1
Energy consumptions in the Petlyuk column and alternate distillation schemes

Distillation sequence	Total heat duty supplied in the reboilers (kWatt)
Petlyuk	604.9
PU-L	626.3
PU-V	607.3
RL	702.4
RV	607.7
RL-U	697.5
RV-U	627.8

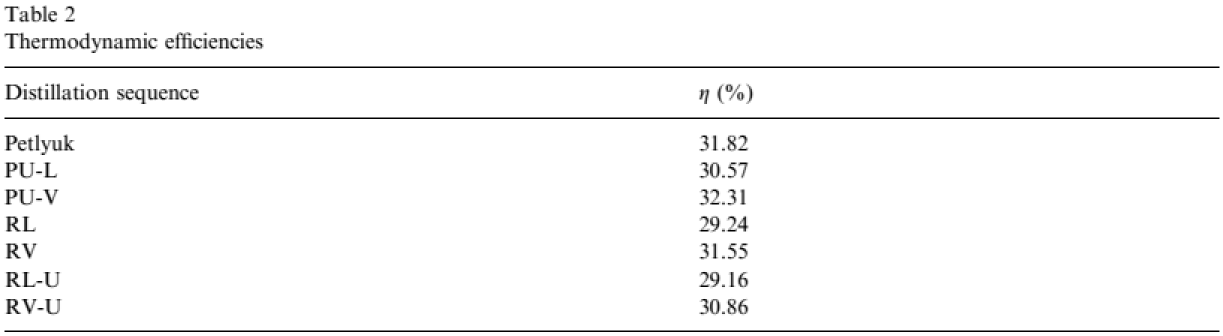


Table 2
Thermodynamic efficiencies

Distillation sequence	η (%)
Petlyuk	31.82
PU-L	30.57
PU-V	32.31
RL	29.24
RV	31.55
RL-U	29.16
RV-U	30.86

Source: Salvador Hernandez et al. (2006)

The paper investigated the various energy requirements for the alternative the scheme and they compared it with the Petlyuk column to find out the thermodynamically efficient system.

U.Can et al. (2002): Paper has the importance in the dynamic field of the distillation column. A rigorous model for the dynamic behavior of the column was developed which allow the model to find out the different failure for the column. Cooling medium supply failure to the condenser and the reflux supply to the column have been discussed in this paper. Different physical effects during the investigation of the column was studied i.e. hydrodynamic effect and mass transfer effect, controlling effect, operational condition on safety, and efficiency of the protective system. In the paper the author has enlisted the failure possibility which causes the overpressure buildup in the system which causes the failure of the system. On the basis of that, a dynamic model has been designed, and a similar condition applied and the system was simulated accordingly. The stimulated result gives the process behavior of the disturbance in the system. These results are very important in the design of the different component in the distillation column whose failure lead to a disaster.

Omar Yildirim et.al (2011): This paper highlighted the significant of the divided wall distillation column in the various field of chemical engineering. Its cost effectiveness and the parallel design complication have been discussed in this paper. It also deals with the application of the divided distillation column in handling the azeotropic, reactive and the extractive distillation. The paper gives an overview of the different control aspect of the divided wall distillation column. These are lead to determine the types of the distillation column used in the industry. In the reactive divided wall distillation column, the reactive unit and the separating unit were integrated in the same column. The paper highlights that, as the number of component to be separated increases the column configuration also increases.

Zuzana Svandova et.al (2008): The objective of this paper was to demonstrate the comparison between the equilibrium and a non equilibrium model during the safety analysis through the HAZOP procedure. This safety analysis mainly focuses on the identification of the hazardous situation during various operating condition. They also analyzed the multiple steady states and their stability. HAZOP analysis makes the process smooth with minimum human error probability. HAZOP procedure along with a mathematical model determined the response of the reactive column at various operating condition. The reliable prediction of the column depends on the complexity of the mathematical model chosen.

William L. Luyben (2012): This paper work in the area of safety analysis of the system. Dynamic simulations were widely used for control of the system although the model does not accurately show the dynamic response. This paper uses an aspen plus for finding the dynamic behavior. The basic radfrac model has been incorporated to the reboiler and the condenser to find the dynamic variation in the system. Proportional controller is use to control the system by manipulating the flow rate. Two types of safety aspect had been analyzed. First- the effect of supply of cooling water to the condenser. Second - higher supply of steam to the reboiler. Finally it was observed that the aspen simulation was not able to predict the rapid pressure changes during the emergency.

H. Z. Kister (2003): This paper is the collection of the facts which are causing the failure of the tower. There are several reasons behind the malfunctioning of the column. Paper highlighted some of the reasons of the failure of the tower. Plugging of the tray active area, coking of the tower, corrosions are various causes which affects the functioning of the tower. There are several reason for the failure of the tower i.e. premature flooding in the reboiler due to sudden rise in liquid level, internal damage, abnormal operational failure like assembly mishap, wrong measurement, explosions, foaming, packing liquid distribution, leaks, failure of the controller, overpressure relief, etc. This valuable effort of the author gives a better insight for the future designing of the tower.

Alessandro Tugnoli et al. (2008): In this work, the author mainly concentrate on the development and design of the layout plan for the better understanding and analyzing the safety performance of the system. It focuses on the inherent safety prospect at different point in the layout design. It presents an integrated index approach to detect the early fault in the system by assessing the early plant layout. The present work in this paper also emphasizes the domino effect of the plant hazard and risk related to this. The paper also highlights the area where protection can be applied. The paper presents the things through the case study of the plan layout to highlight the value of inherent safety measures in the layout design. An index approach for the detection of the domino effect developed and index based assessments achieved. The application of the index in the case study demonstrates the effectiveness of the approach.

Yahya Chetouani (2013): A fault detection of the industrial processes is very important to study safety, reliability and the component availability. The paper approaches the development of the fault detection system for the non linear system. The performance of the FD system was tested in the real distillation column in laboratory and the result is reported in the paper. The paper used the Bayes classification theory to detect the fault. It is a statistical approach. The study shows that the combination of the ANN model and the Bayes classifier solves the underlying problem of fault detection. The experimental result shows the one layer perceptron which provide a better view for the normal system and a faulty system. The current work on this paper also highlighted the limited availability of the model in the chemical industry, so the current model used here is promising in the future study of the reliability of the system for the fault detection and safety measurement.

CHAPTER -3 THEORY AND METHODS

3.1 Reliability:

The probability that an item will perform the required function for the stated period of time at stated condition is known as the reliability of the item. The above definition brought several feature of the reliability i.e. reliability is a time and conditional function. It is also signifies as the function of the failure.

Basically failures are of different type. Some failures are operational in nature, some failures are on demand, certain failures are before demand and after demand ends. The operational failure related to the equipment that is worked continuously where as other failure are one which is related to the failure on demand.

3.2 Reliability functions and hazard rate:

If n equipments operate without replacement, then after time t the numbers which have survived and failed are $n_s(t)$ and $n_f(t)$, respectively, and the probability of survival, or reliability, R (t) is:

$$R(t) = 1 - \frac{n_f(t)}{n}$$

Expression for the instantaneous failure rate, or failure rate as a function of the number of equipments surviving, z (t) is:

$$Z(t) = \frac{1}{n-n_f}\frac{dn_f(t)}{dt} = -\frac{1}{R(t)}\frac{dr(t)}{dt} = \frac{d[\ln R(t)]}{dt}$$

Z (t) is also called the 'hazard rate', or the 'failure rate'.

The cumulative hazard function H (t) is:

$$H(t) = \int_0^t z(t)dt$$

By integrating reliability R (t) we get the reliability equation as:

$$R(t) = \exp\left(-\int_0^t z(t)dt\right) = \exp\left[-H(t)\right]$$

R (t) is called the 'reliability function.

3.3 The Bathtub Curve:

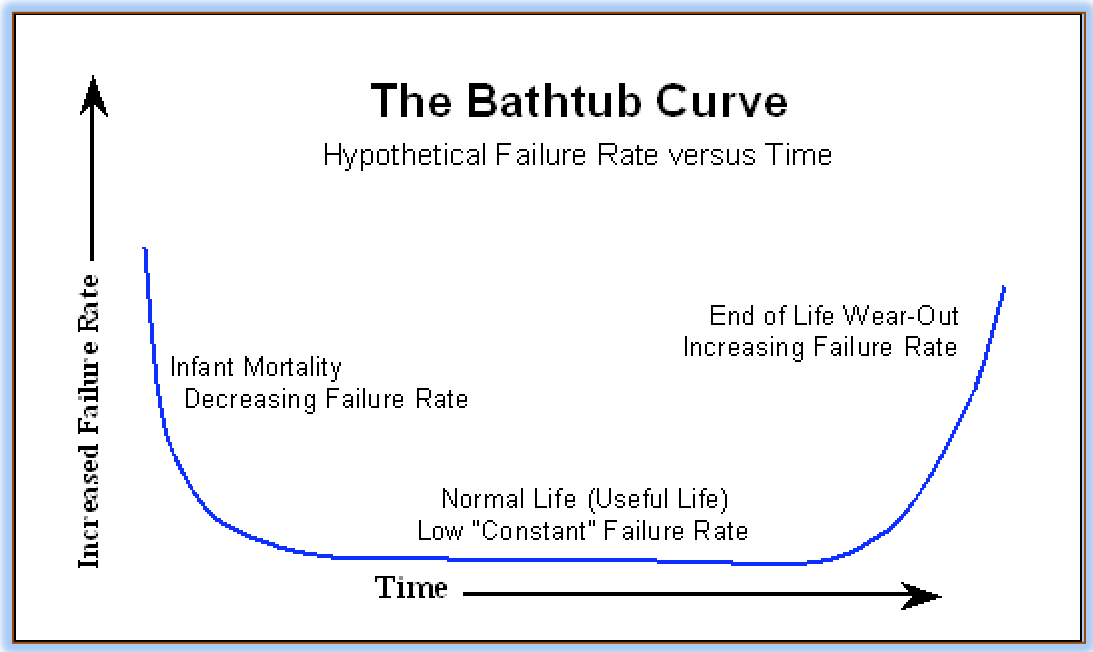


Figure-8: Bathtub Curve Diagram

Source: Internet (www.weibull.com)

Life of the different units classified into three basic periods. These three periods distinctly show the reliability of the different unit in the system. Bathtub curve is the graphical representation of the failure rate verses the time curve. The name bathtub is due to its similarity with the shape of bathtub. The curve initially has the high decreasing failure rate which is the first period of the curve. It signifies that the equipment at its early life have significant tolerance to failure. Its probability of failure is minimum at is early life. After that the curve gets flatten and shows the constant rate of failure. This is basically the useful life of the equipment. The maximum time spent in this period. After passing through the useful life the curve starts to show the increasing rate of failure. The maximum chances of failure of the equipment are in wear out phase of the equipment. Thus the three distinct periods can be interpreted in the bathtub curve.

Early Life Period

Early life period is known as the decreasing failure rate (DFR) or the infant mortality rate. It is the initial stage of the failure and causes mainly due to the defect in the equipments; this may be due the faulty manufacture defect or the welding defect which causes the equipment failure. This failure rate shows the rapid decreasing rate in short span of time.

Normal Life (useful life)

This life is known as the constant failure rate (CFR).the easy detection of the failure is very difficult in this period and it has longest time span. Due to its long life period it is very important for the purpose of the study of the reliability of the system.

End of Life (Wear Out)

It is known as the increasing failure rate (IFR). This can be characterized by increasing rate. It is happen after spending a lifetime. This period is also a small and usually identified by wear out of the system due to fatigue, aging, friction, corrosion etc.

TABLE-1 Bathtub Curve

	Characterized by	Caused by	Reduced by
Burn in	DFR	Manufacturing Defects: Welding Flaws, Cracks, Defective parts, poor quality control, contamination, Poor workmanship	Burn in Testing Screening Quality Control Acceptance testing
Useful Life	CFR	Environment, Random Loads, Human Error, “Acts Of God”, Chance events.	Redundancy Excess strength
Wear Out	IFR	Fatigue, Corrosion, Aging, Friction, Cyclical Loading.	Derating, Preventive maintenance Part Replacement, Technology

Source – An Introduction to reliability and maintainability engineering by Charles E.Ebeling

3.4 Mean Time to Failure

This is an important reliability measure and it can be obtained by using any of the following formulas:

$$\mathrm{MTTF} = \int_{0}^{\infty} \mathrm{R(t)dt}$$

Or,

$$\mathrm{MTTF} = \int_{0}^{\infty} \mathrm{tf(t)dt}$$

MTTF is the mean time to failure and R (t) is the reliability function.

CFR Model

Constant failure model is the model having the constant rate of failure in their useful life. This is also known as the exponential probability distribution and it has an important role in the reliability study of the system. Many systems show this constant failure rate and the CFR model is used for analyzing it. Mostly random and chance events are associated with it

For CFR Model assuming

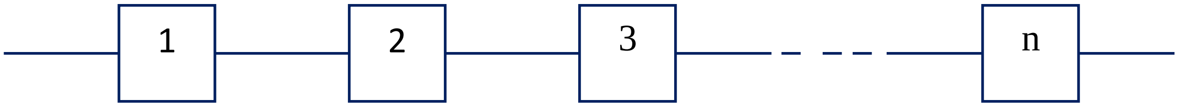
$$\lambda(t) = \lambda, t \geq 0, \lambda > 0$$

$$\text{MTTF} = \int_{0}^{\infty} e^{-\lambda t}\, dt = \frac{1}{\lambda}$$

Series Configuration

A system can be arranged in the two ways either in the series configuration or the parallel configuration. In the series configuration the entire component in the series must work for the system to work .if either of the two serially related component fail the system will fail or not respond.

Reliability block representation of the series relationship



Since reliability is the probability, so system reliability can be determine by the component reliability

E_1 = the event that component 1 does not fail

E_2 = the event that component 2 does not fail

$P(E_1) = R_1$ and $P(E_2) = R_2$

Where

R_1 = the reliability of component 1

R_2 = the reliability of component 2

Therefore

$R_s = P(E_1 \cap E_2) = P(E_1)\,P(E_2) = R_1 R_2$ (assuming that the two component are independent.)

Generalizing to n mutually independent component in the series

$$\mathrm{R_s = R_1 \times R_2 \times \ldots\ldots \times R_n \leq \min\{R_1(t), R_2(t) \ldots\ldots R_n(t)\}}$$

Where

$$0 < R_i(t) < 1$$

In general for CFR model

$$\mathrm{MTTF_s} = \frac{1}{\sum_{i=1}^{n} \lambda} = \frac{1}{\sum_{i=1}^{n} \frac{1}{\mathrm{MTTF}}}$$

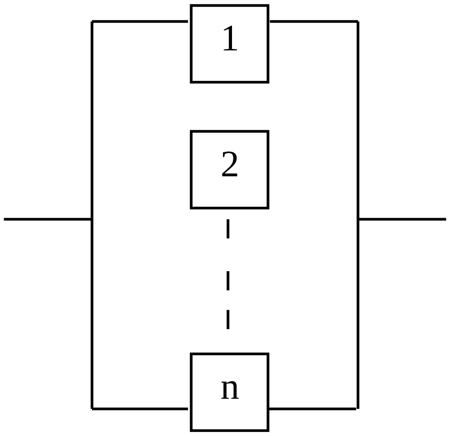
Where

MTTF = mean time to failure of the ith component.

Parallel Configuration

Two or more components are in parallel, or redundant, configuration if all units must fail for the system to fail. If one or more units operate, the system continues to operate.

Block Diagram of the Parallel System



System reliability for n parallel and independent component is found by taking 1 minus the probability that all n component fail (i.e. the probability that at least one component does not fail)

For two component

$R_s = P\,(E_1 \cup E_2) = 1 - P(E_1 \cup E_2)^c = 1 - P(E_1^c \cap E_2^c) = 1 - P(E_1^c)P(E_2^c) = 1 - (1 - R_1)(1 - R_2)$

On generalizing

$$R_s(t) = 1 - \prod_{i=1}^{n}[1 - R_i(t)]$$

For The CFR model

$$R_s(t) = 1 - \prod_{i=1}^{n} [1 - e^{-\lambda_i t}]$$

Where

λ_i = The failure rate of the ith component

For the system having two independent component

$$MTTF = \frac{1}{\lambda_1} + \frac{1}{\lambda_2} - \frac{1}{\lambda_1 + \lambda_2}$$

3.5 K- out- of –n Redundancy

A generalization of n parallel component occurs when a requirement exists for k out of n identical and independent components to function for the system to function.

Where

$$\kappa \leq n$$

If

$\kappa = 1$ (Complete redundancy occurs)

$\kappa = n$ (Components are in series)

Reliability of the system can be obtained through binomial probability distribution.

$$P(x) = (C_x^n) R^x (1 - R)^{n-x}$$

Where

x successes (nonfailure) obtain from n component

$$R_s = \sum_{x=k}^{n} P(x)$$

R_s is the reliability of the system

For the CFR system

$$\mathrm{MTTF} = \int_{0}^{\infty} \mathrm{R_s(t)dt} = \frac{1}{\lambda}\sum_{x=k}^{n}\frac{1}{x}$$

3.6 OBJECTIVE

As the distillation column has wide range of application, it is very necessary to find out its chances of failure and its corresponding reliability. My current work is also aimed in the same direction.

1. To identify various components in the Petlyuk column and the divided wall distillation column whose chances of failure are more and to find their failure rates from literature.

2. To find the reliability of the individual sub systems and the overall reliability of the two columns assuming constant failure rate (CFR) model.

3. Compare reliabilities of the two systems and graphical analyses of reliability with the time.

4. To find criterion/conditions, if any, for more reliable system.

Petlyuk column:

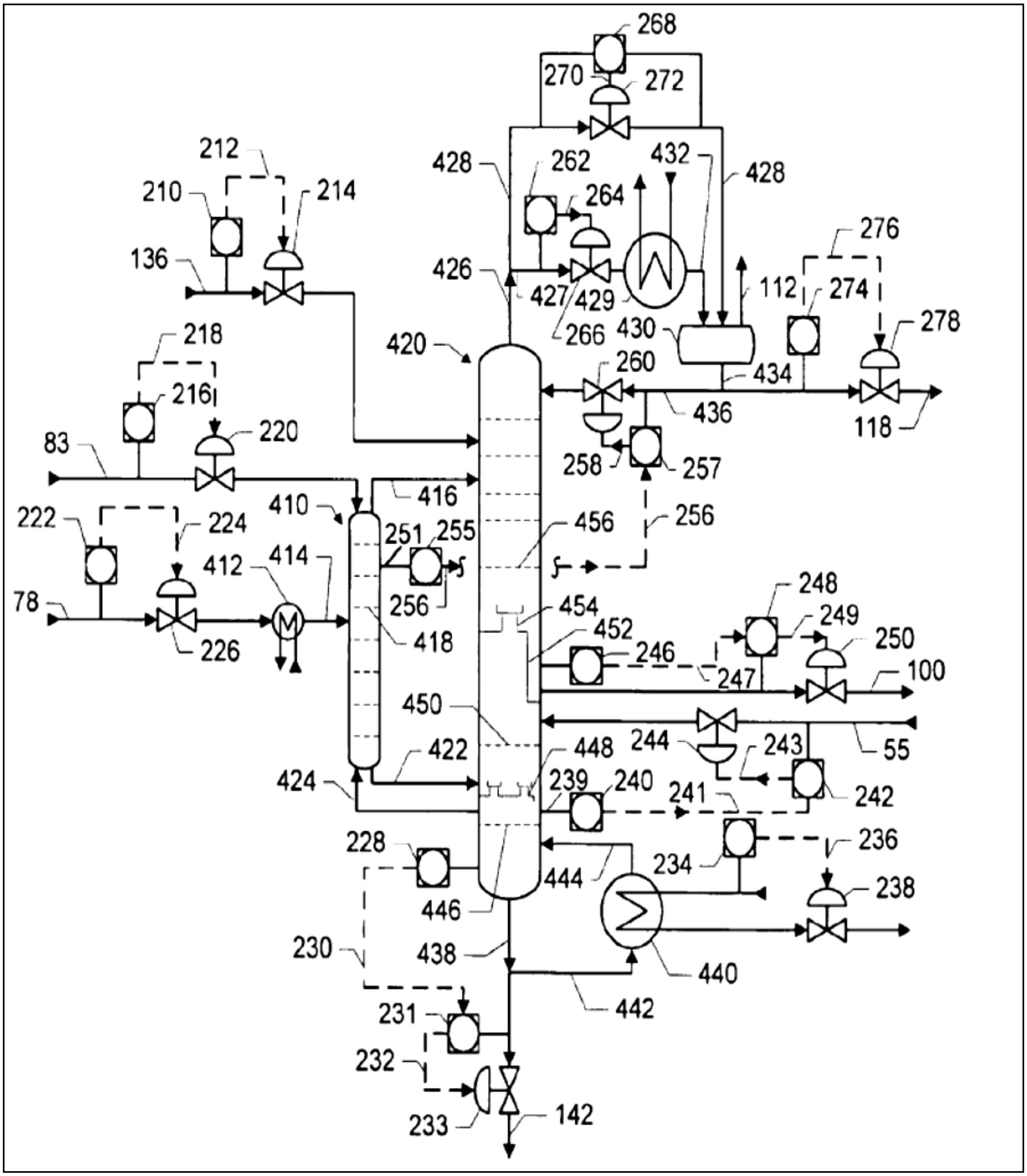


Figure-9: A Petlyuk Column and its accessories

Petlyuk column and the divided wall distillation column consists of several components whose chances of failure is more. The system basically made up of many minor components all together within a major one but determining probability of failure of those miniature components is very cumbersome. So during the analysis only major component has been selected as one unit with a unique MTTF.

3.7 Identification of the component of the Petlyuk column:

TABLE -2 List of component of petlyuk column

Serial No.	Component No.	Name of the component	Serial No.	Component No	Name of the component
1.	83	Conduit	18.	233	Regulating valve
2.	78	Main feed conduit	19.	142	Conduit
3.	222	Flow controller	20.	446	Plate
4.	226	Regulating valve	21.	438	Conduit
5.	216	Flow controller	22.	251	Temperature device
6.	220	Regulating valve	23.	255	Temperature controller
7.	136	Conduit	24.	440	Reboiler
8.	210	Flow controller	25.	442	Conduit
9.	214	Regulating valve	26.	444	Conduit
10.	410	Prefractionator	27.	234	Flow controller
11.	412	Pre heat exchanger	28.	238	Regulating valve
12.	414	Conduit	29.	239	Temperature Device
13.	416	Conduit	30.	240	Temperature controller
14.	418	Plate	31.	242	Flow controller
15.	420	Main Column	32.	244	Regulating valve
16.	422	Conduit	33.	448	Accumulator plate
17.	424	Conduit	34.	55	Conduit

35.	426	Conduit	49.	246	Level controller
36.	428	Conduit	50.	248	Flow controller
37.	450	Plate	51.	250	Regulating valve
38.	228	Level controller	52.	100	Conduit
39.	231	Flow controller	53.	454	Accumulator Plate
40.	257	Flow controller	54.	428	Conduit
41.	260	Regulating valve	55.	432	Conduit
42.	434	Conduit	56.	429	Condenser
43.	436	Conduit	57.	427	Conduit
44.	118	Conduit	58.	266	Regulating valve
45.	274	Flow controller	59.	262	Pressure controller
46.	278	Regulating valve	60.	268	Pressure controller
47.	112	Conduit	61.	272	Regulating valve
48.	430	Overhead receiver			

Divided Wall Distillation Column:

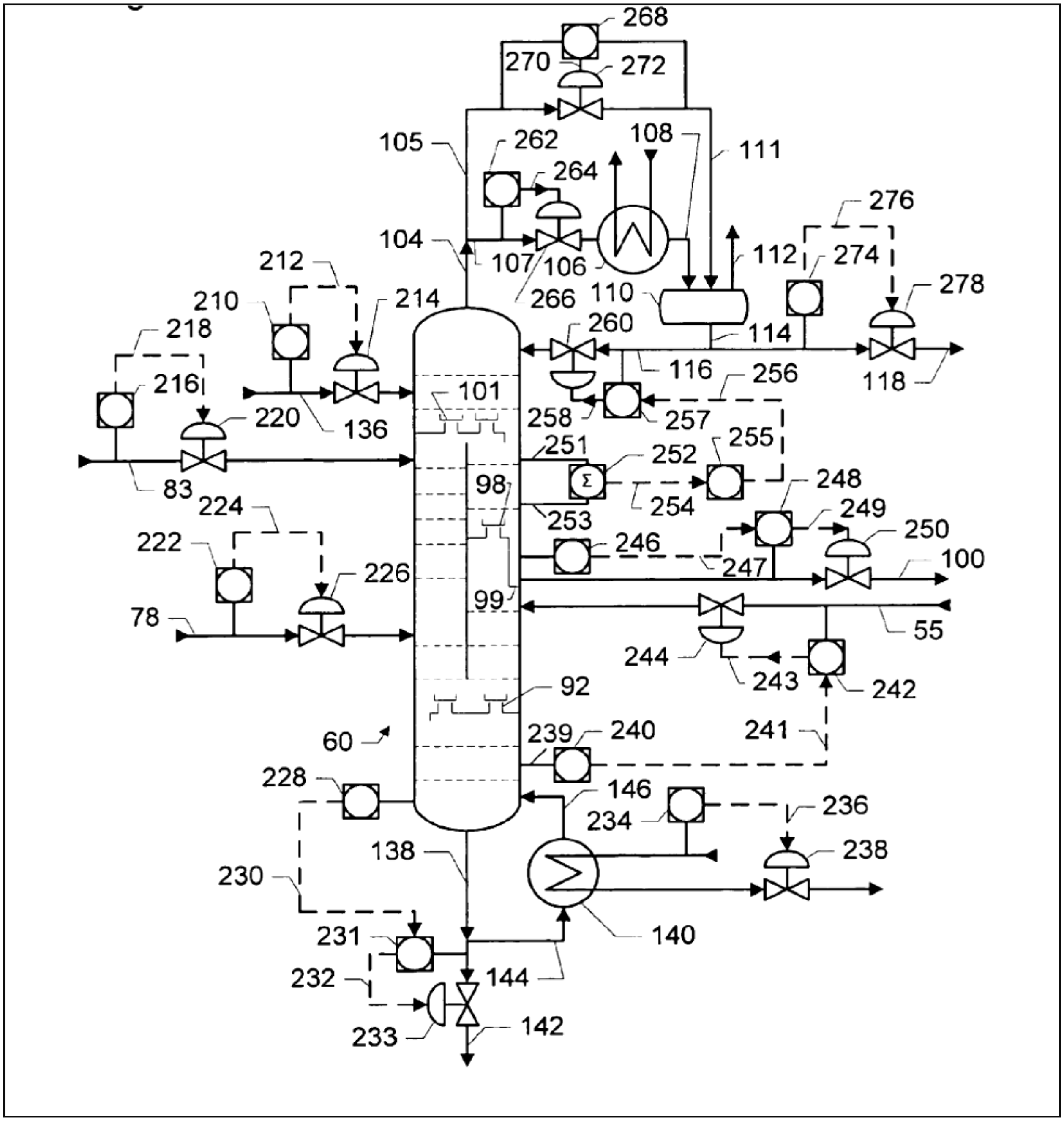


Figure-10: A Divided Wall Distillation Column and its accessories

3.8 Identification of the component of the divided wall distillation column:

TABLE-3 List of the component of the divided wall distillation column

Serial No.	Component No.	Name of the component	Serial No.	Component No.	Name of the component
1.	210	Flow controller	25.	274	Flow controller
2.	212	Output signal	26.	276	Output signal
3.	214	Regulating valve	27.	278	Regulating valve
4.	136	Conduit	28.	251	Temperature controller
5.	216	Flow controller	29.	252	Summing device
6.	218	Output signal	30.	253	Temperature controller
7.	220	Regulating valve	31.	254	Output signal
8.	83	Conduit	32.	255	Controller
9.	78	Conduit	33.	256	Output signal
10.	222	Flow controller	34.	257	Flow controller
11.	224	Output signal	35.	258	Output signal
12.	226	Regulating valve	36.	260	Reflux regulating valve
13.	104	Vapor conduit	37.	228	Level controller
14.	105	Pressure conduit	38.	230	Output signal
15.	268	Pressure controller	39.	231	Flow controller
16.	270	Output signal	40.	232	Output signal
17.	272	Regulating valve	41.	233	Regulating valve
18.	111	Pressure conduit	42.	142	Conduit
19.	106	Condenser	43.	138	Conduit
20.	107	Conduit	44.	144	Conduit
21.	262	Pressure controller	45.	140	Reboiler
22.	264	Output signal	46.	238	Regulating valve
23.	266	Regulating valve	47.	236	Output signal
24.	112	Conduit	48.	234	Flow controller

49.	114	Conduit	58.	146	Conduit
50.	116	Reflux conduit	59.	239	Temperature device
51.	118	Conduit	60.	240	Temperature controller
52.	241	Output signal	61.	247	Output signal
53.	242	Flow controller	62.	248	Flow controller
54.	243	Output signal	63.	249	Output signal
55.	244	Regulating valve	64.	250	Regulating valve
56.	55	Conduit	65.	100	Conduit
57.	246	Level controller			

CHAPTER -4 RESULTS AND DISCUSSION:

The Petlyuk column and the divided wall distillation column are very complex unit in which there are several components whose failure can lead to failure of the overall unit. To reduce the complexity of the unit I have divided the Petlyuk column and the divided wall distillation column into several smaller systems and calculated their overall failure rate.

4.1 Constant failure rate of components of smaller sub system of Petlyuk column:

TABLE -4

System-1 Level controller unit (Component no.-228,231,233,142 in the Figure-9)

Device	Component ID	No. of Component	λ_i
Level Controller	228	1	10×10^{-6}
Flow Controller	231	1	85×10^{-6}
Valve	233	1	30×10^{-6}
Conduit	142	1	0.658×10^{-6}

$$\sum \lambda_1 = 125.658 \times 10^{-6}$$

Since the system-4 (component no.-246,248,250,100 in Figure-9) is identical with the system-1.hence its value of failure rate is not calculate separately.

System	λ_i
System-4	$\sum \lambda_4 = 125.658 \times 10^{-6}$

TABLE-5 System-2 Reboiler unit (Component no.-442,444,234,238,440 in Figure-9)

Device	Component ID	No. Of Component	λ_i
Conduit	442,444	2	1.316×10^{-6}
Flow Controller	234	1	85×10^{-6}
Regulating Valve	238	1	30×10^{-6}
Reboiler	440	1	306×10^{-6}

$\sum \lambda_2 = 422.316 \times 10^{-6}$

TABLE-6 System-3 Flow controller unit (Component no.-240, 242, 244, 55 in Figure-9)

Device	Component ID	No. of Component	λ_i
Temperature Controller	240	1	11×10^{-6}
Flow Controller	242	1	85×10^{-6}
Regulating Valve	244	1	30×10^{-6}
Conduit	55	1	0.658×10^{-6}

$\sum \lambda_3 = 126.658 \times 10^{-6}$

TABLE-7 System-5 Temperature controller unit (Component no.-255,257,260 in Figure-9)

Device	Component ID	No. of component	λ_i
Temperature Controller	255	1	11×10^{-6}
Flow Controller	257	1	85×10^{-6}
Regulating Valve	260	1	30×10^{-6}

$\sum \lambda_5 = 126 \times 10^{-6}$

TABLE-8 System-6 Condenser unit (Component no.-262,266,427,432,429 in Figure-9)

Device	Component ID	No. of Component	λ_i
Pressure Controller	262	1	30×10^{-6}
Regulating Valve	266	1	30×10^{-6}
Conduit	427,432	2	1.316×10^{-6}
Condenser	429	1	420×10^{-6}

$$\sum \lambda_6 = 481.316 \times 10^{-6}$$

TABLE-9 System-7 Pressure controller unit (Component no.-428,112,268,272 in Figure-9)

Device	Component ID	No. of component	λ_i
Conduit	428,112	2	1.316×10^{-6}
Pressure Controller	268	1	30×10^{-6}
Regulating Valve	272	1	30×10^{-6}

$$\sum \lambda_7 = 61.316 \times 10^{-6}$$

TABLE-10 System-8 Flow Controller unit (Component no.-251,436,260,274,258 in Figure-9)

Device	Component ID	No. of Component	λ_i
Conduit	251,436,260	3	1.974×10^{-6}
Flow Controller	274	1	85×10^{-6}
Regulating Valve	258	1	30×10^{-6}

$$\sum \lambda_8 = 116.974 \times 10^{-6}$$

TABLE-11 System-9 Heat Exchanger unit (Component no.-78,414,222,226,412 in Figure-9)

Device	Component ID	No. of Component	λ_i
Conduit	78,414	2	1.316×10^{-6}
Flow Controller	222	1	85×10^{-6}
Regulating Valve	226	1	30×10^{-6}
Heat Exchanger	412	1	40×10^{-6}

$$\sum\lambda_9 = 156.316 \times 10^{-6}$$

TABLE-12 System -10 Flow Controller unit (Component no. - 83,216,220 in Figure- 9)

Device	Component ID	No. of Component	λ_i
Conduit	83	1	0.658×10^{-6}
Flow Controller	216	1	85×10^{-6}
Regulating Valve	220	1	30×10^{-6}

$$\sum\lambda_{10} = 115.658 \times 10^{-6}$$

Since the system-11 (component no.-136,210,214 in Figure-9) is identical with the system-10. Hence its value of failure rate is not calculated separately.

System	λ_i
System-11	$\sum\lambda_{11} = 115.658 \times 10^{-6}$

This system contains mainly controllers, valves and the pipeline. After certain time of operation, each of the components has the different failure probability due to various reasons. The pipe system has the chances of failure due to corrosion, internal high pressure, buckling caused by the high pressure, stress related effect etc. whereas the valves has the various environmental as well as non-environmental factor associated to it like seal leakage due to embrittlement, poppet failure , vibration ,shock etc. Apart from these, there are many other environmental conditions responsible for the failure of the system. The overall failure rate includes such factors as well as the other responsible factors. The failure rate also includes the extreme value selected in case of the range of the value.

4.2 Smaller sub system of divided wall distillation column:

TABLE-13 System-1 Flow Controller (component no.-210,214.136 in Figure-10)

Device	Component ID	No of component	λ_i
Flow controller	210	1	85×10^{-6}
Regulating valve	214	1	30×10^{-6}
Conduit	136	1	0.658×10^{-6}

$$\sum \lambda_1 = 115.658 \times 10^{-6}$$

Since system-2 flow controller (component no.-216, 220, 83 in Figure-10) and system-3 flow controller (component no.-78,222,226 in Figure-10) are identical system to the system-1.hence its value is not calculated separately.

system	λ_i
System-2	$\sum \lambda_2 = 115.658 \times 10^{-6}$
System-3	$\sum \lambda_3 = 115.658 \times 10^{-6}$

TABLE-14 System-4 Pressure controller (component no.-104,105,111,268,272 in Figure-10)

Device	Component ID	No of component	λ_i
Vapor conduit	104	1	0.658×10^{-6}
Pressure conduit	105,111	2	1.316×10^{-6}
Pressure controller	268	1	28×10^{-6}
Regulating valve	272	1	30×10^{-6}

$$\sum \lambda_4 = 59.974 \times 10^{-6}$$

TABLE-15 System-5 Condenser (component no.-106,107,262,266 in Figure-10)

Device	Component ID	No of component	λ_i
Condenser	106	1	420×10^{-6}
Pressure conduit	107	1	0.658×10^{-6}
Pressure controller	262	1	28×10^{-6}
Regulating valve	266	1	30×10^{-6}

$$\sum \lambda_5 = 478.658 \times 10^{-6}$$

TABLE-16 System-6 Flow controller unit (Component no.-112,114,118,116,274,278 in Figure-10)

Device	Component ID	No of component	λ_i
Conduit	112,114,118	3	1.974×10^{-6}
Reflux conduit	116	1	0.658×10^{-6}
Flow controller	274	1	85×10^{-6}
Regulating valve	278	1	30×10^{-6}

$$\sum \lambda_6 = 117.632 \times 10^{-6}$$

TABLE-17 System-7 Temperature controller unit (Component no.-251,253,255,257,260 in Figure-10)

Device	Component ID	No of component	λ_i
Temperature controller	251,253	2	22×10^{-6}
Controller	255	1	28×10^{-6}
Flow controller	257	1	85×10^{-6}
Reflux regulating valve	260	1	30×10^{-6}

$$\sum \lambda_7 = 165 \times 10^{-6}$$

TABLE-18 System-8 Level controller unit (Component no.-228,231,233,142 in Figure-10)

Device	Component ID	No of component	λ_i
Level controller	228	1	10×10^{-6}
Flow controller	231	1	85×10^{-6}
Regulating valve	233	1	30×10^{-6}
Conduit	142	1	0.658×10^{-6}

$$\sum \lambda_8 = 125.658 \times 10^{-6}$$

TABLE-19 System-9 Reboiler unit (Component no.-138,144,146,140,238,234 in Figure-10)

Device	Component ID	No of component	λ_i
Conduit	138,144,146	3	1.974×10^{-6}
Reboiler	140	1	306×10^{-6}
Regulating valve	238	1	30×10^{-6}
Flow controller	234	1	85×10^{-6}

$$\sum \lambda_9 = 422.974 \times 10^{-6}$$

TABLE-20 System-10 Temperature controller unit (Component no.-240, 242, 244, 55 in Figure-10)

Device	Component ID	No of component	λ_i
Temperature controller	240	1	11×10^{-6}
Flow controller	242	1	85×10^{-6}
Regulating valve	244	1	30×10^{-6}
Conduit	55	1	0.658×10^{-6}

$$\sum \lambda_{10} = 126.658 \times 10^{-6}$$

Since system-11 level controller unit (Component no.-246,248,250,100 in Figure-10) is identical with the system-8 .hence its value is not calculated separately.

System	λ_i
System-11	$\sum \lambda_{11} = 125.658 \times 10^{-6}$

In the two units being considered in the present work, i.e. Petlyuk column and a divided wall distillation column; feed flow rate is controlled by using several components. Failure of any of these components can reduced the quality of the product which ultimately may or may not be treated as failure of the distillation column according to our requirement. The failure may be operational or of other type. The system complete shutdown when it faces a major problem. The study of reliability of these components vis-à-vis distillation column signifies that how long our system can survive. Although, several researchers (A. Jimenez et.al.) have shown that the divided wall distillation column has an edge over the Petlyuk column with respect to the capital cost and the energy requirement. However, it appears that no one has attempted to compare reliabilities of the two column configuration. Apart from above enlisted component the system has pumps attached to it whose failure will also affect the overall reliability of the two columns.

4.3 Analysis of the Pump System:

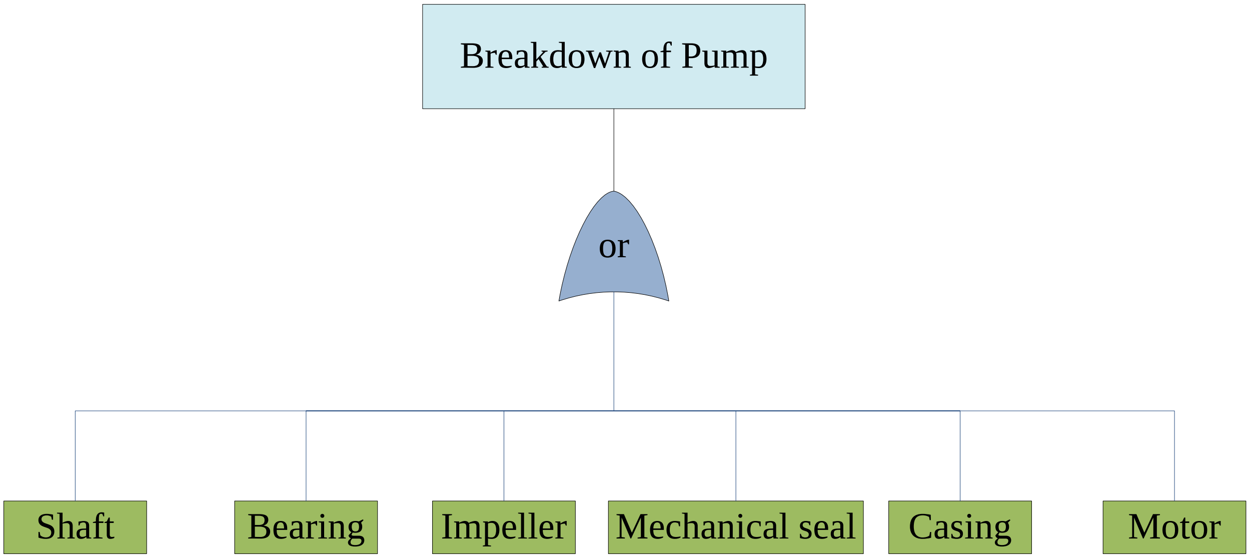


Figure-11 Fault tree diagram of the pump

Pump (basically a mechanical component) are being used in the various field in our society. They are of different type based on the operating condition and in the different environment. The pump mainly consists of the shaft, bearing, impeller, seal, casing and the motor. These components of the pump can be failed by too many reasons like shaft deflection, corrosion, motor failure, external leakage due to seal failure, mechanical noise due to debris in the impeller etc. However, for the satisfactory operation of a pump, all the six components have to function simultaneously (Figure-11). Obviously, change in failure rate of any one component, i.e., shaft, bearing, impeller, mechanical seal, casing, motor, etc alters failure rate of the pump. Similarly, being a component of the distillation system, the overall reliability of pump will also affect the reliability of the distillation column. In the Petlyuk column and the divided wall distillation column pumps are used for the various purposes. For the supply of the feed, a feed pump is used at the supply line and vacuum pump is used in the upper section of the column.

TABLE-21 Pumps used in Petlyuk column:

Pump type	Number of pumps	λ (one unit)	Overall λ
Feed pump	4	300×10^{-6}	1200×10^{-6}
Vacuum Pump	8	20×10^{-6}	160×10^{-6}

$$\sum \lambda_{\text{pump system1}} = 1360 \times 10^{-6}$$

TABLE-22 Pump used in the divided wall distillation column:

Pump type	Number of pumps	λ (one unit)	Overall λ
Feed pump	2	300×10^{-6}	600×10^{-6}
Vacuum Pump	4	20×10^{-6}	80×10^{-6}

$$\sum \lambda_{\text{pump system2}} = 680 \times 10^{-6}$$

Reliability of the pump system:

Reliability of pump in Petlyuk column	Reliability of pump in DWC
$\mathbf{e^{-(1360 \times 10^{-6})t}}$	$\mathbf{e^{-(680 \times 10^{-6})t}}$

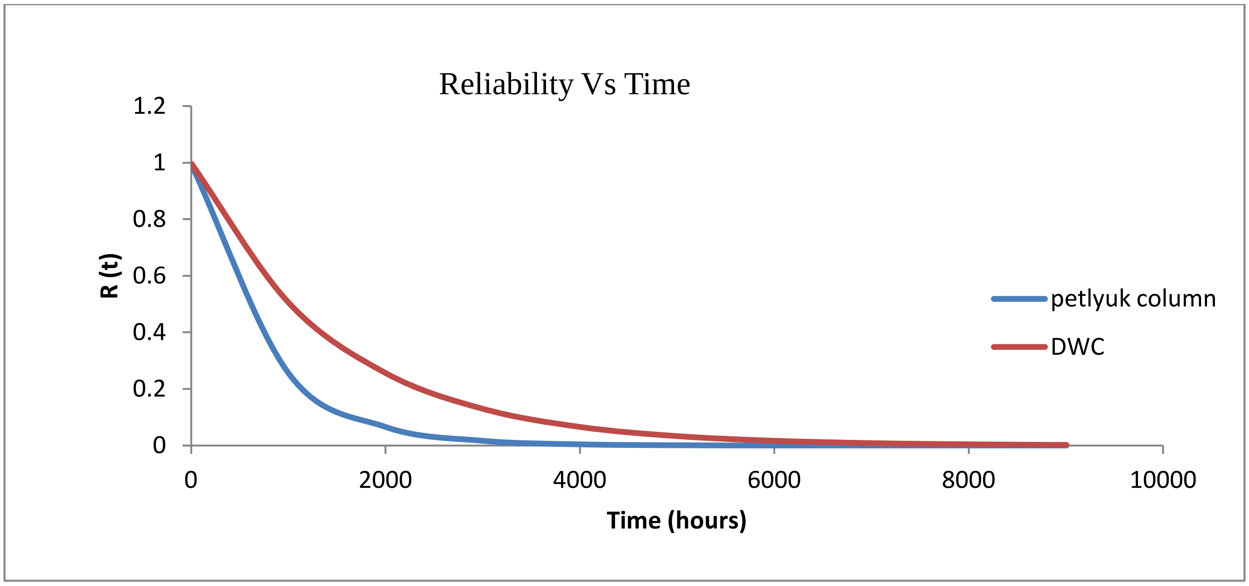


Figure -12 Reliability Vs time graph for pump

Discussion about the comparison of pump system:

After calculating reliabilities of the two distillation columns it has been found that the reliability of the pump system used in the divided wall distillation column is more than the reliability of the Petlyuk column. It signifies that the probability of the failure of the pumps used in the Petlyuk column is more due to the higher number of pump used in it. This analysis also gives an idea to develop a plan to analyses the capital equipment replacement and the economical feasibility of repairing it. It also gives an idea about the time after which the system has higher chances of failure.

The graph (figure-12) shows that the initially the reliability of the pump used in Petlyuk column decreases sharply as compared to that used in divide wall distillation column. After a long time, about 6000 hours (250 days) onwards, reliabilities of both pumps falls down to almost zero indicates that it is highly improbable that either of the two pumps can run without any failure for more than 250 days. Thus from the figure it is clear that pumps used in petlyuk system needs more cost as compare to the divided wall distillation column for their maintenance.

4.4 Internal Structure of the Distillation column:

The internal structure of the distillation column consists of the trays, downcomer, weirs, dividing wall, fabricated materials etc. these components are directly in contact with the feed. Chances of their failure are more due to the corrosion, plugging of the holes and the coking. As the time passes they reduce the efficiency of the column which, below certain limit, may be considered as column failure. The failure of the column may also be caused by the tower flooding, instability and the poor separation. It also get damaged due to the water induced pressure surge, insufficient mechanical resistance, breakage in the tray, poor assembly, flow induced vibration etc. These things lead to the overall failure of the column. Failure of these internal structures is very important for the purpose of the reliability study of the distillation column.

Internal component of Petlyuk column:

TABLE-23 List of internal component in the distillation column

Name of Component	Number of Component in first Column	Number of Component in second Column
Bubble cap tray	25	25
Downcomer	25	25
Weir	25	25
Holes	1385	1385

TABLE-24 Failure rate of internal component of Petlyuk column:

Name of Component	λ_i	No of Component	Overall λ_i
Bubble cap tray	57.078×10^{-6}	25	334.573×10^{-6}
Downcomer	22.831×10^{-6}	25	570.775×10^{-6}
Weir	22.831×10^{-6}	25	570.775×10^{-6}

$$\sum \lambda_{\text{internal system1}} = 1476.123 \times 10^{-6}$$

Assumption: If 10% of the bubble caps on a tray fail the system considered to be failed

TABLE-25 Internal component of the divided wall distillation column:

Name of Component	Number of Component in first Column
Bubble cap tray	50
Downcomer	50
Weir	50
Dividing wall	1

TABLE-26 Failure rate of the internal component of DWC

Name of Component	λ_i	No of Component	Overall λ_i
Bubble cap tray	57.078×10^{-6}	50	451.283×10^{-6}
Downcomer	22.831×10^{-6}	50	570.775×10^{-6}
Weir	22.831×10^{-6}	50	570.775×10^{-6}
Dividing wall	11.416×10^{-6}	1	11.416×10^{-6}

$$\sum \lambda_{\text{internal system2}} = 1604.249 \times 10^{-6}$$

Reliability of the internal assembly:

Reliability of internal assembly in Petlyuk column	Reliability of internal assembly in DWC
$\mathbf{e^{-(1476.123 \times 10^{-6})t}}$	$\mathbf{e^{-(1604.249 \times 10^{-6})t}}$

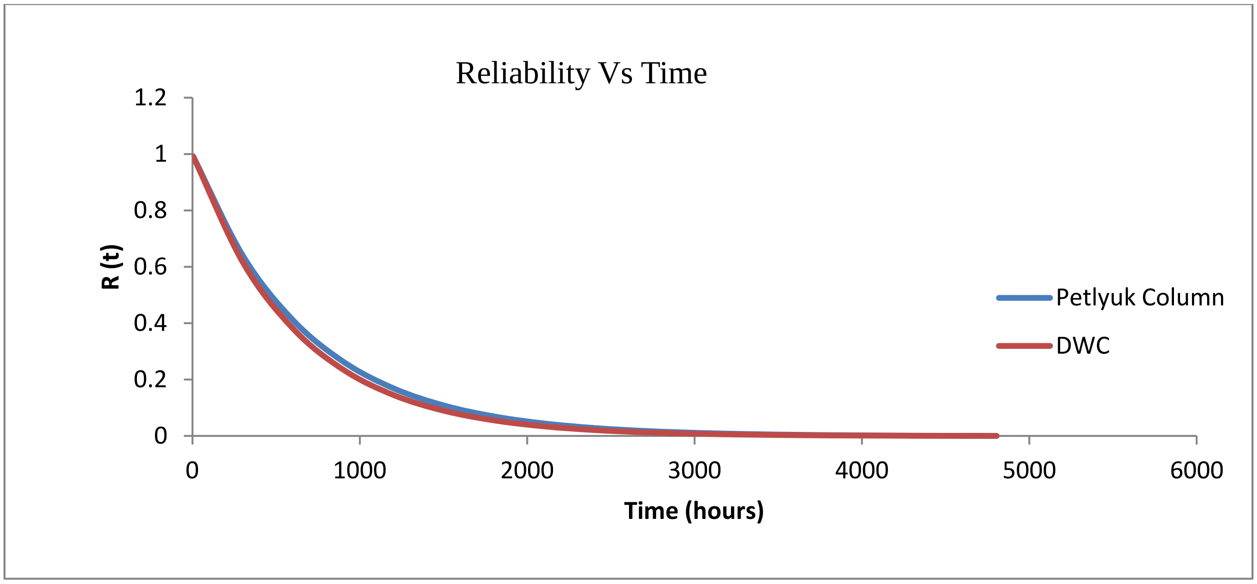


Figure -13 Reliability Vs Time graph of internal assembly

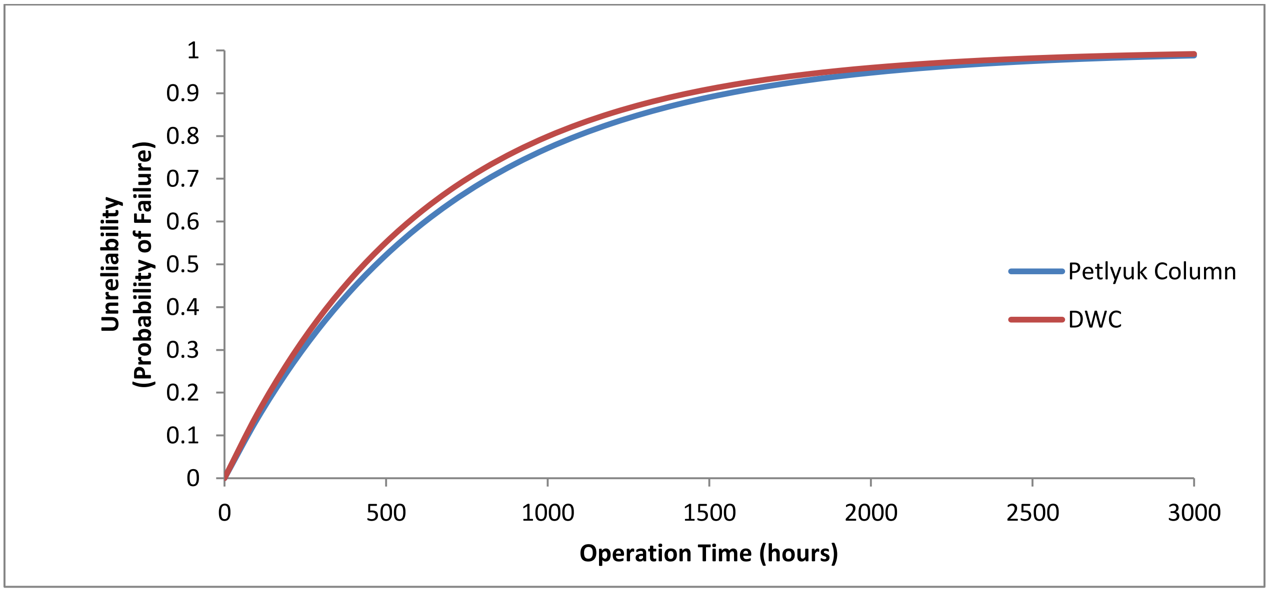


Figure-14 Unreliability Vs Time graph for two columns

Discussion about the comparison of internal assembly system:

The internal assembly is very complicated in both systems. Due to presence of dividing wall inside the divided wall distillation column it has higher operating risk. Despite of less reliable pumping system of the Petlyuk column, the reliability of the internal of Petlyuk column is more than the divided wall distillation column. The additional structure inside the DWC such as the dividing wall, welding, joints, etc increases its probability of failure. Its need extra precautions during the fabrication and better regulation for the thermal stress and the load stress of the system.

Initially both the system have almost same reliability and chances of failure of both the systems are equal, but after 500 hours onwards the divided wall distillation column internal assembly shows less reliability with respect to the Petlyuk column. It may be because of the extra stress on the wall due to more number of plates attached to it. However after about 2000 hours internal assemblies of both the columns have almost same reliability i.e. equal vulnerability to a failure.

4.5 Comparison between the reliability of the Petlyuk column and the divided wall distillation column:

TABLE-27 List of systems

Petlyuk column		**Dwd column**	
SYSTEM	λ_i	SYSTEM	λ_i
System-1	125.658×10^{-6}	System-1	115.658×10^{-6}
System-2	422.316×10^{-6}	System-2	115.658×10^{-6}
System-3	126.658×10^{-6}	System-3	115.658×10^{-6}
System-4	125.658×10^{-6}	System-4	059.974×10^{-6}
System-5	126.000×10^{-6}	System-5	478.658×10^{-6}
System-6	481.316×10^{-6}	System-6	117.632×10^{-6}
System-7	61.316×10^{-6}	System-7	165.000×10^{-6}
System-8	116.974×10^{-6}	System-8	125.658×10^{-6}
System-9	156.316×10^{-6}	System-9	422.974×10^{-6}

System-10	115.658×10^{-6}	System-10	126.658×10^{-6}
System-11	115.658×10^{-6}	System-11	125.658×10^{-6}
System-internal	1476.123×10^{-6}	System-internal	1604.249×10^{-6}
System-pump	1360×10^{-6}	System-pump	680.000×10^{-6}

$\sum \lambda_{\text{overall system}} = 4809.651 \times 10^{-6}$ $\sum \lambda_{\text{overall system}} = 4253.435 \times 10^{-6}$

Overall reliability of the system:

Reliability of Petlyuk column	Reliability of Divided Wall Distillation Column
$\mathbf{e^{-(4809.651 \times 10^{-6})t}}$	$\mathbf{e^{-(4253.435 \times 10^{-6})t}}$

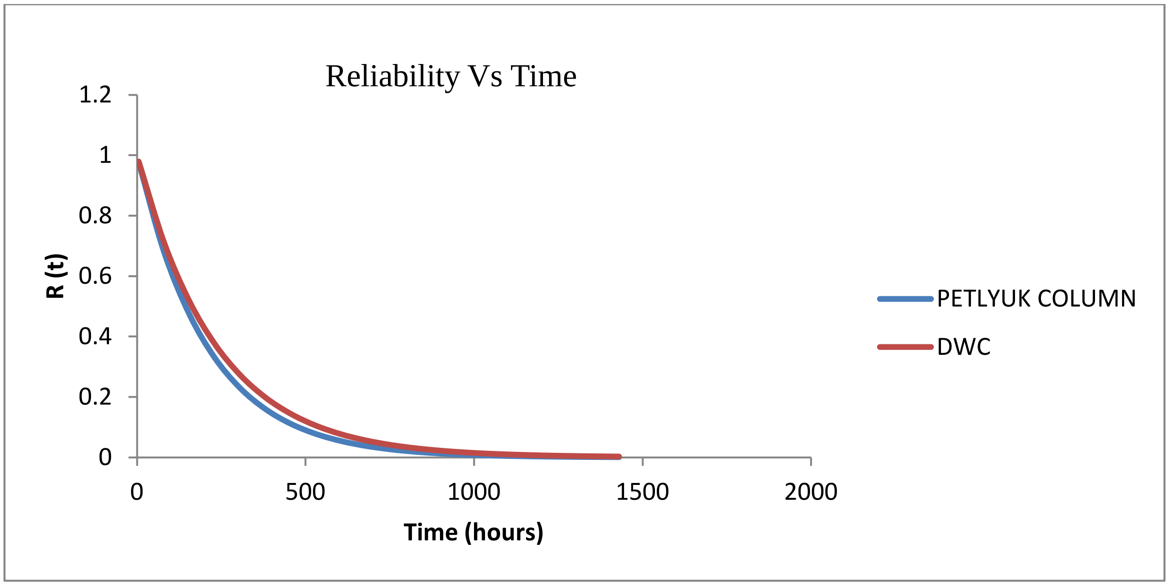


Figure -15 Reliability Vs Time graph for two columns

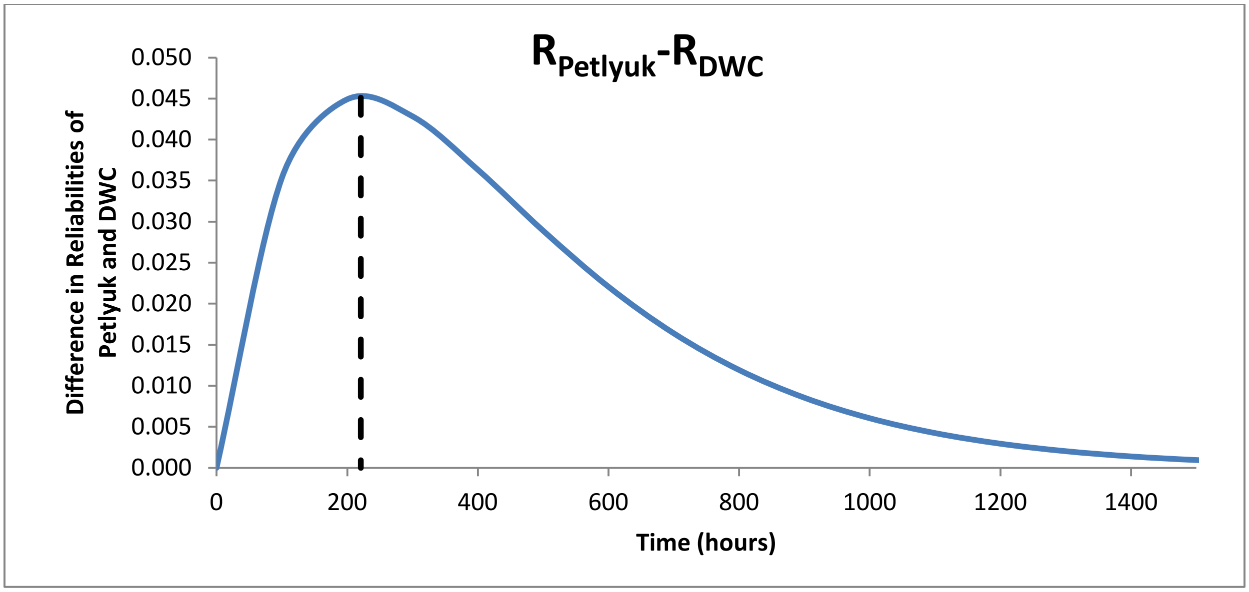


Figure-16 Difference in reliability Vs Time graph for two columns

Overall Reliability:

The overall reliability of the divided wall distillation column is more than the Petlyuk column. It is because of the fact that Petlyuk column, having two different columns with connecting piping, may be more prone to risk of failure and hence becomes less reliable system. Although the divided wall distillation column has extra vulnerability due to complexity in internal fabrication but overall it is more reliable due to presence of only one column. Many authors have already mentioned in various papers about the cost and energy saving in the divided wall distillation column. This reliability analysis of the system also indicates that the divided wall distillation column has an edge over Petlyuk column due to its less operating and other associated failure chances.

In the above graph (Figure-14) we can see that the both the system has almost equal reliability but from Figure-14 it is clear that the difference in reliability is maximum at about 221 hours of operation. However, by this time, reliabilities of DWC and Petlyuk columns decrease to very low values i.e. 0.35 and 0.39, respectively. Statistically these values indicate that if 100 units each of DWC and Petlyuk columns are installed, 65 DWC and 61 Petlyuk columns will experience a failure during 221 hours of operation. Also, as the operating time increases the gap between their reliabilities decreases and after almost 1000 hours onwards they have the almost equal reliability.

CHAPTER-5 CONCLUSION AND RECOMMENDATIONS:

5.1 Conclusion:

This is the first contribution dealing with the reliability analysis of the fully thermally coupled (Petlyuk Column) and the divided wall distillation columns. In the process of determining the reliability of the two columns the system analysis approach was used. Thus the columns were divided into various crucial components (systems) whose chances of failure is more. Reliabilities of individual systems were determined by considering failure rates of various components being used in the system and then the reliability of the entire column was determined. In this process, failure rate data was collected from handbooks, data books, and research papers and components of same make were considered for both the columns. These failure rates include, more or less, all the factors which are responsible for the failure of a component. The overall reliability of the system shows that the divided wall distillation column is slightly more reliable than the Petlyuk column.

The graphical analysis is also on the expected line. In the case of reliability of the internal assembly, the Petlyuk column is more reliable because of its simpler structure. However, due to less reliable pumping system of Petlyuk column, its overall reliability decreases considerably. The result of the above study is on the expected line. Earlier studies about DWC indicate that it is cost effective and energy efficient. The present reliability study of these columns in juxtaposition with the earlier studies will give a better prospect for the future designing of the divided wall distillation columns and the establishment of the plant.

5.2 Recommendations:

- In the present work components of same make were considered for both the columns. In future, a detailed analysis of reliability of each column with various possible combinations of components (of different make) can be done.
- Maintainability of various components used in these columns can also be included in the reliability analysis.
- Operating cost and the maintenance cost require for satisfactory operation of these columns can also be studied.

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