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Distillation Column-Modelling, Control and Optimization -A Review

Ganesh RM*
Assistant Professor, Nandha Engineering College, (Autonomous), Erode, Tamilnadu, India.
Mail Id: ramganesh024@gmail.com

Dr. Manoharan S
Professor, Karpagam College of Engineering, (Autonomous), Coimbatore, Tamilnadu, India.

Marimuthu C N
Professor Nandha Engineering College, (Autonomous), Erode Tamilnadu, India.

Senthil J
Professor Nandha Engineering College, (Autonomous), Erode Tamilnadu, India.

Abstract:

Industrial Chemical Process are normally multivariable in nature with resolute interactions between loops. Due to the interactions and multivariable in nature, these processes need the design and implementation of efficient control system. Distillation column, a multivariable interactive process plays a vital role in the separation and purification of several products in chemical industries. Uncontrolled distillation column has adverse effects due to interactions in column, variation in process gain, reduction in purity of the final product and finally affects the stability and performance of the distillation unit. Various control and optimization methods are reviewed in this paper along with different types of distillation columns. Most of the cases will normally focus on the optimal performance of the process in column, purity of the final product and stable working. Avoiding of faults that occur in column is also a major part reviewed in the article.

Keywords: Multivariable Process, Distillation column, Controllers, Fault Tolerance, Optimization.

I. Introduction

Distillation column process is a highly nonlinear multivariable chemical reactive process which is used for the separation of product components [1]. They are normally operated based on the temperature equilibrium, material balance control, quality control of top/bottom products and constraints along with enormous energy consumption [2]. Major methods include reactive distillation, cyclic distillation, cryogenic distillation, heat integrated distillation and membrane distillation techniques. Modelling plays a major role in distillation column for proper understanding of static and dynamic responses [3]. Safety constraints are mainly focused since temperature and pressure in the column should be maintained for effective operation of the column [4]. Furthermore, column control has to be simplified for proper startup and shutdown so that heat recovery and proper reflux operation can be obtained. While considering material balance control, arrangement of the control technique has to be performed in the same direction of flow of components in the column [5]. In the next case of controlling the composition, it is necessary to control the feed flow, reflux flow, top/bottom products and tray dynamics [6]. Response time is a major criterion to be looked after when the set-point tracking is executed in the column. This also supports in attenuation of disturbances that occur in the column since operating conditions under the influence of disturbances along with interactions in loops increases the complexity of design [7]. Even though we focus on column working with stability and performance of desired points, efficiency of the column is reduced in cases where gravity changes occur. In order to achieve more operating efficiency, intensifying of process model is carried out in most of the cases. Generally, a system is said to be single input single output (SISO) if it has single actuating signal and single process output. At the same time, if the system has ore than one actuating signal and process output, then it is said to be a multi input multi output system (MIMO).

II. Literature Survey

Separation of components from a mixture is generally done by distillation. Determination of organic constituents are performed by micro distillation columns [8-9] but efficiency is related to the number of stages of distillation as well as the separation phases [10]. Other cases include thermodynamic equilibrium attention, mass transfer, absorption governed phases in distillation columns are used in content separation [11]. Heat integrated distillation columns, membrane distillation, reactive column, cyclic distillation, cryogenic distillation process and optimal design for propylene/propane separation are generally used distillation columns for separation purpose [12]. Membrane distillation includes advantages of having acceptable efficiency at low cost and maintenance in turn finds application where processing of food materials and waste segregation is performed [13]. Design aspects of membrane distillation for cleaning waste and desalination were reported with control strategies that helps in maintaining the quality and quantity of the final product [14].

Controlling a distillation column is based on the rejection of disturbance, effect of interactions in loops, performance of the column and decoupling control implemented by decentralizing method [15-16]. Multivariable centralized control is used in inverted decoupling where functions are obtained with respect to the control elements which is independent of complexity and system size [17]. Conventional decoupling method is employed where interactions are minimum and compensated output is produced for each loop when controller is tuned [18]. Regulating the purity of a product from distillation column is discussed with feedforward and state feedback controller [19]. Usage of cascade control for process is discussed where the feedback and feedforward control fail in reducing the effects of load disturbances and interactions before attaining the setpoint [20]. Stability and performance improvement of the process is better with parallel cascade control strategy [21]. Time delay systems are controlled by using additional loops in the secondary controller that resulted in satisfactory performance [22].

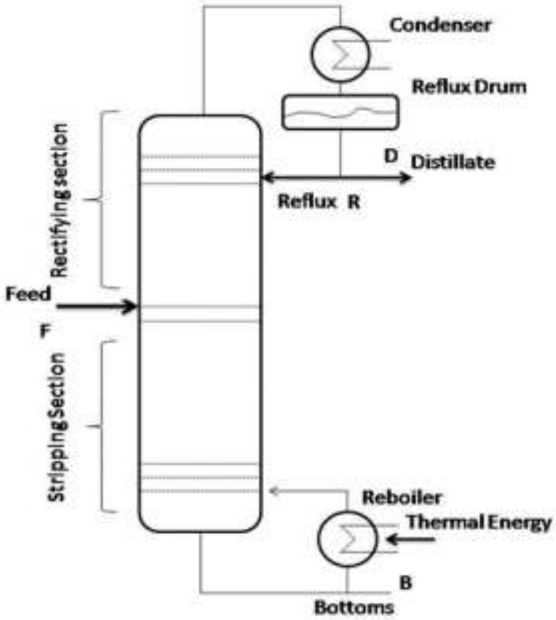

Fig: 1 Distillation Column

Precautionary measures: Modelling of a system is to be dealt with utmost care since it helps in understanding the steady state and dynamic behavior of the process. It also helps in selecting and testing of various control algorithms to the system during simulation as well as in real time implementation.

Robust control techniques have to be adopted for controlling a nonlinear process due to the effect of interactions and presence of uncertainties in process parameters that changes dynamically. If the error persists for a long time, then product at the outlet cannot be achieved with high purity. In this case, a least value of Integral Time Absolute Error (ITAE) has to be obtained with proper tuning and optimization technique.

III. Modelling and designing of controllers for distillation column

Normally, chemical process has a sequential design approach based on the performance, economic conditions and dynamic operability. Modeling of a distillation column is done in three basic categories such as fundamental modelling, empirical modelling and hybrid modelling/grey box modelling. Conventional controllers are used for the controlling of distillation column where number of inputs and outputs with interactions in loops are accounted [23]. PID controllers, auto tuning PID controllers, Fuzzy logic controllers and Adaptive Neuro fuzzy controllers can be employed for taking care of time and frequency domain operating values [24]. Optimization methods include robust techniques, dynamic methods, embedded and controllability-based optimization. Design of controllers can be taken care based on controllability indicators and optimization. Priori design includes linear and non-linear analysis, design with simple calculations which are almost easy to compute. This method also incorporates the impact of specific steady state conditions only and not the entire working range of distillation process [25-26]. Control of a reactive distillation column is a tedious task due to the presence of nonlinearities and complex interactions in the column. PID controller with different strategies including Dynamic Matrix Control, Quadratic Control were employed in controlling the column which resulted in maintaining the product purity in a desired range [27].

Distillation column has numerous control variables and a manipulated variable which is associated with a controlled variable [76-77]. It becomes mandatory for the design of a controller which satisfies the servo as well as the regulatory responses despite of the disturbances that occur in the process. It is essential for linearizing the input-output of a process for better improved performance. Controllers include PID, Auto Tuning PID, Neural Network, Fuzzy logic, Adaptive controllers, Model Predictive, Internal Model controllers and Dynamic Matrix controllers are employed for a class of SISO and MIMO systems [28].

IV. Optimization of distillation column

Optimization of the process is mainly depended on the mathematical modelling and identifying the degrees of freedom since the number of primary controlled variables has to be equal to the number of degrees of freedom [29]. It is also mandatory to predict and employ necessary steps to avoid the effects of disturbances on the process. Disturbances that affect the cost function of the process has to be eliminated to the fullest for efficient working. Optimization of the column also involves the selection of number of trays, feed, operating condition, performance function, cost effectiveness, energy reuse and complexity of the design. Assumptions of process parameters while working with a distillation column will produce satisfactory results in continuous and discrete modes. Two approaches were employed in literature where modelling and optimizing a distillation column is carried out. First is the Mixed Integer Non-linear Programming (MINLP) and second is Generalized Disjunctive Programming (GDP) [30]. Other methods such as Generalized Benders Decomposition (GDB) [31], Outer Approximation (OA) [32] are iterative methods that solves the problems in linear and non-linear problems by using lower and upper bound variables with integrating the subproblems under single constraint. Extended Cutting Plane method (ECP) [33] is used in solving problems based on successive linearization's. Boundary Value Method (BVM) is used in determining the reflux ratio and separation of homogeneous mixture [34]. Reversible Distillation Model (RDM) assumes that heat can be transferred to and from a column with no difference in temperature [35]. Rectification body method (RBM) is used in the determination of minimum energy requirements of the specified composition [36]. Driving Force Method (DFM) is a simple graphical method based on the minimum energy needed as driving force for separation of compounds [37]. Shortest Stripping Line approach (SSL) is used where the separation boundary are decided by the local longest residue with minimum energy consumption [38]. Stochastic optimization techniques involve Genetic Algorithm based optimization (GA), Simulated Annealing (SA), Simultaneous Perturbation Stochastic Approximation (SPSA), including the basic advantages of simple algorithms, measurements of objective functions, tolerance to noise in function, increase in operating efficiency [39-40]. Imperial competitive algorithm (ICA), Particle swarm optimization (PSO) and Ant colony optimization (ACO) are some of the fastest optimization algorithms used in distillation column for increased performance and stable operating conditions [41-42].

Fault tolerant control is employed for maintaining high reliability of the process for operating in long duration [43]. It is also vital for a distillation process to be in acceptable boundaries while working along with better performance. Reconfiguration control is a strategy through which recovery of a faulty system is carried out under nominal condition. Both active and passive control mechanisms are employed for the process based on performance requirements [44-46]. Usage of adaptive controllers for reconfiguration in non-linear process yields best results.

V. Distillation column types and applications

Binary distillation column is the base for separation process in which the top and bottom products are obtained by heat supply and reflux control [47].

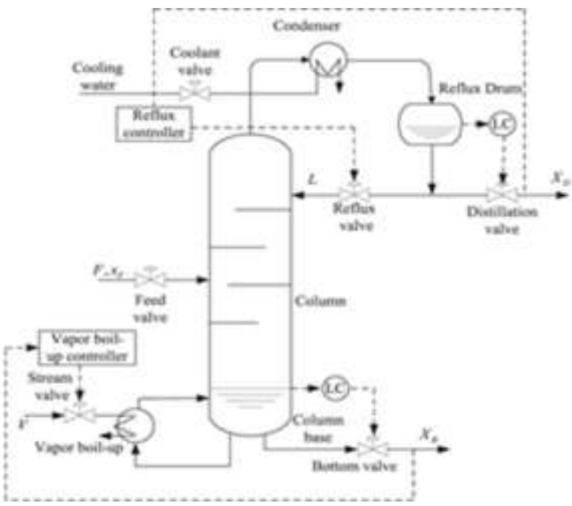

Fig 2: Binary Distillation Column

Major distillations include reactive and catalytic distillations. Reactive distillation is the one in which reaction and distillation is done in a single vessel. It is explored in terms of hydrogenation, etherification and esterification. Distillation process is used in synthesis of carbon acetates, methyl and ethyl acetate, and esterification of fatty acids. Esterification involves relatively high temperature points which leads to the reduction of catalyst life [48].

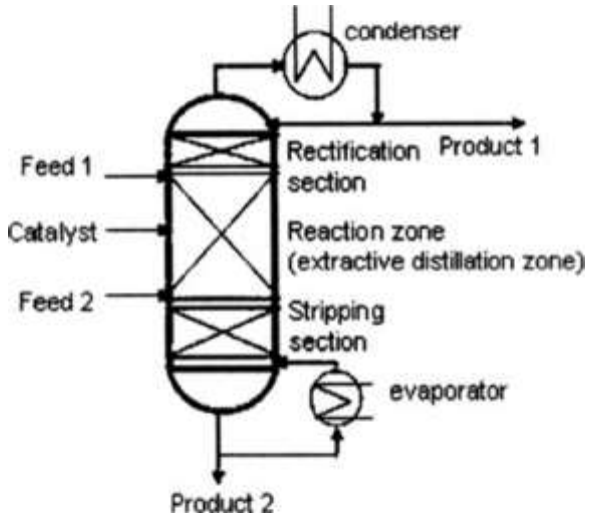

Fig 3: Reactive Distillation Column

Maintaining temperature in this process is highly complicated and addressed in many researches. Transesterification is beneficial in the production of butyl acetate and oxalates where water formation is evaded. Hydrolysis of methyl acetate and alcoholics of alkyl halides are done with reactive distillation along with dehydrohalogenation reactions.

Etherification is particularly the synthesis of acetates from the given mixture by ion exchange. Separation of isobutene from hydrocarbon mixture is carried out by extractive distillation. Hydrogenation process carried out with low temperatures and super atmospheric pressures is used in production of benzene, cyclopentane, synthesis of iso-octane from isobutylene and removal of methyl acetylene from hydrocarbon streams.

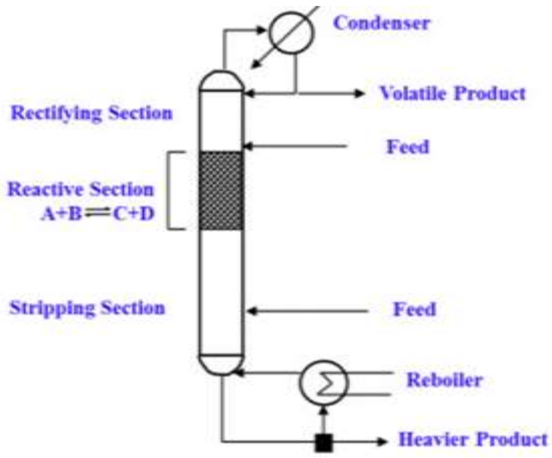

Fig 4: Catalytic Distillation Column

Hydration and dehydration by reactive distillation for production of ethylene glycol is also a considerable application due to the exothermic heat reaction and optimized reflux control. Synthesis of acetic acid, carbonylation of methanol, dimethyl ether, polymer production was addressed extensively with various control factors in reactive distillation column.

Catalytic distillation is used in alkylation of benzene/toluene with propylene, benzene with ethylene in dry gas and synthesis of linear alkyl benzene. Recovery of chemicals deals with high cost and complex control strategies for a distillation column application. Additional reactions include production of phenol, propylene, tetramethyl and vinyl acetate [49].

Divided wall columns are the one which finds its use in minimum energy consumption applications with less or no disturbances [50].

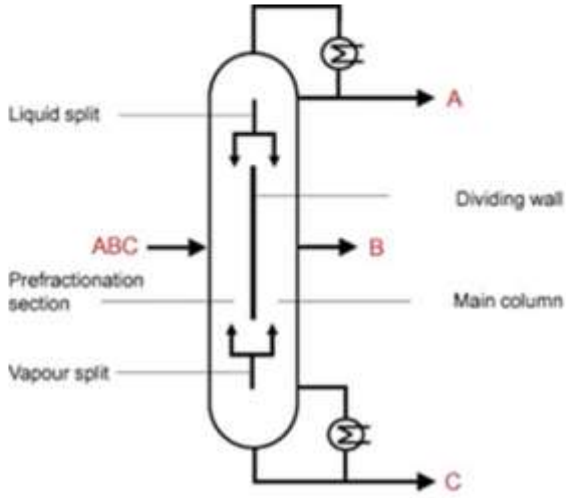

Fig 5: Dividing wall column

A vertical wall is constructed in the middle of the column as shown in figure 4 and the vapor that comes from the stripping section splits into the walls of the column. At the top of the wall a total liquid trap out tray collects all the liquid coming down from the rectifying section. A portion of the liquid is fed to the top of the prefractionator side of the wall. The rest is fed to the top of the side stream wall and so it requires only one wall and two heat exchangers which reduces the initial cost and also helps in reducing the energy consumption.

Heat integrated columns are low pressure columns where the heat is integrated in the column by using a single heat exchanger. In this column, the product temperature and pressure is measured and maintained in tray from bottom to the top. Temperature of the base tray is determined by the reflux drum pressure and total tray pressure drop and the composition of the product. There is no need of auxiliary reboiler or condenser in this type of columns. Energy consumption will be on the higher side as well as working with these types of column is flexible. High pressure columns are used for certain applications where the tray temperature is higher and the product composition is of high density [51-52].

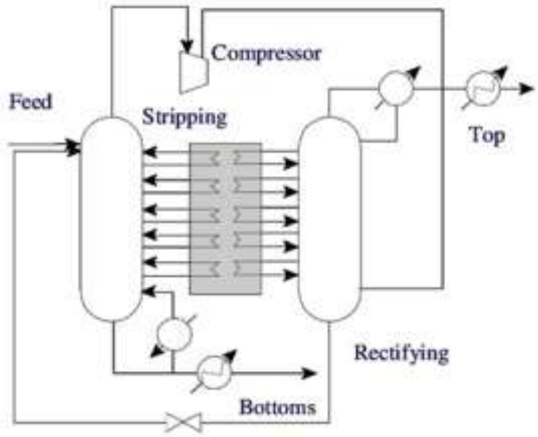

Fig 6: Heat Integrated Distillation Column

Other types include membrane distillation [53], cyclic distillation [54] and cryogenic distillation [55] are used in heat transfer and separation applications. Membrane distillation uses thermal transfer, low cost and high energy efficient operation which finds its application in small scale units, food processing industries and waste management techniques [56]. Vacuum force distillation, capillary force distillation, zero gravity distillation, micro structured distillation, high gravity distillation and centrifugal force distillation finds use in determining the reaction rate, correlation coefficients of mixtures, sample collection, concentration and phase separation applications [57-60].

Distillation models include wood and berry model (WB), Industrial scale polymerization (ISP) reactor model, Vinate and Luyben (V-L) model, Skogested model [61-63].

The application of separating natural gas and liquid involves multiple separators for separating the oil and water from gas wells. Pressure in the dividers has to be reduced for maximum gas recovery and for stabilization of crude oil. Compression of processed gas to high pressure is done to maximize the value of processing equipment's in further stages. Variations of volatility in the feed components is normally high in this separation. Divided wall columns find more effective application for this process due to its low pressure working and ease in processing with high temperature handling capacity. Heating and cooling also takes much lesser efforts for controlling when compared with conventional system. Low compression and effective operation make the cost analysis compatible with lesser initial investments.

Another application is the separation of benzene from hydrocarbon products. This separation plays a vital role in extraction of cooking oils, vegetable oils, aromatic and non-aromatic compounds, feedstock from gasoline. In this vital process, use of columns for separation involves cost analysis with high initial investment and operational cost, complexity of the process and output products. Energy efficient columns are employed for this separation since boiling points of components vary in rapid manner.

VI. Case studies

Distillation column finds its place in all chemical separation process with required moderations according to the type of components used, variation in control strategies, performance measures and stability considerations. Safety and cost-effective working of the column is considered to be a major concern related to the applications.

Use of sensors, valves and actuators, tray dynamics, disturbances, effects and rejection of disturbances, controller selection, tuning, control strategy, interactions and decoupling constraints are to be considered for a column under work. Case studies are discussed as a part of the research work for better understanding of the distillation column use in various chemical processing units. As a study of column working with crude oil separation, an atmospheric distillation column, a vacuum distillation column and stabilization column is presented in the discussion [64].

Atmospheric distillation column is the place where crude fractionation takes place. The figure represents the model of a column with 26 trays, a partial condenser in the absence of a reboiler. Feed is given at the 26th tray and steam input is applied. Various products are obtained at the outlets including naphtha, kerosene, diesel and atmospheric gas oil. The main products of the column include condenser vapor (wet gas) and a condensate (LSR-Light Straight Run) [64]

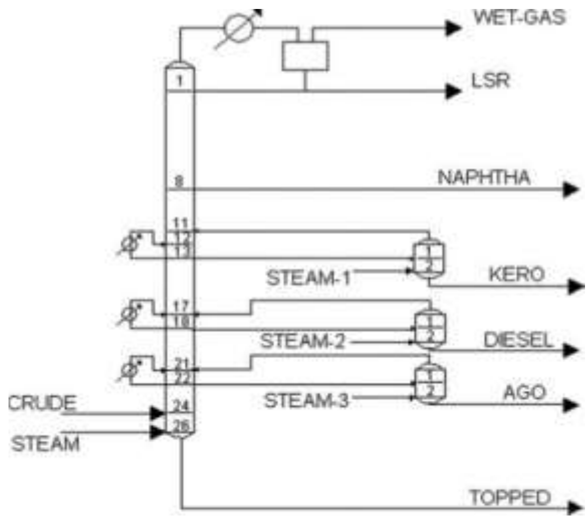

Fig 7: Atmospheric distillation column

Starting with a vacuum distillation column, mainly focusses on fractionating the least volatile components of crude. Crude is fed at the bottom part of the column (topped) and the upper part is let to vacuum. Products of the column include light vacuum gas oil (LVGO) and heavy vacuum gas oil (HVGO), residues as mentioned in figure 8 [64].

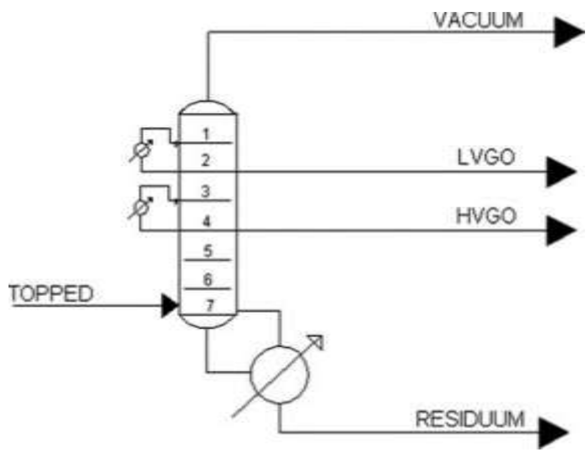

Fig 8: Vacuum Distillation Column

Stabilization column separates the most volatile components from crude where the condensate is fed at the tray 10 and the product from the column are vapor from the condensate (off gas), condensate and stabilized LSR [64].

For analysis purpose, an equilibrium model is framed by defining the mass balance, energy balance, molar concentrations of liquid and vapor and equilibrium of phases. It becomes mandatory for characterize the components since different fractions of crude produces various products.

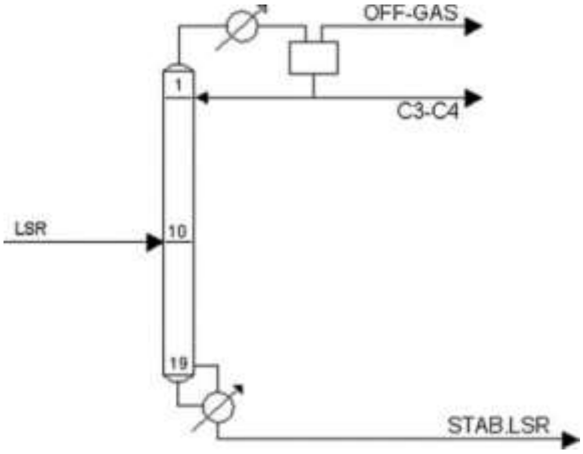

Fig 9: Stabilization column

Inclusion of thermodynamic properties such as density, enthalpy, entropy, viscosity, boiling point and molecular weights needs more attention with degrees of freedom for a distillation column [65].

Optimization of the column depends on the operation variables and model variables which are related to the operational constraints and internal/external flows. Decision variables include steam input, feed flow, temperature of the column product, pressure and reflux. In simulation point of view, design specifications, operating specifications and product specifications are considered which are said to be in direct influence with the product output [66]. As the complexity of the column under work remains high during fractionation, initial values for column stabilization has to be defined under known boundaries. Sensitivity analysis is performed for the column product outlet ensuring the stability and performance remain at higher/satisfactory levels [67].

General comments on working with crude distillation are presented in the following segment. If the reflux ratio of the column remains high, operating/separation efficiency will be better. If the operating pressure is low, then the relative volatility will be high and separation process remains easier. If the heater temperature is higher, percentage of vaporization will be higher in the outlet. In this case, heat recovery will also be better [68]. Dealing with bulk chemicals such as ethylene, propylene, ethane and propane, constraints respect to column sizes, internal alignments, temperature and pressure has to be taken care [69]. Air distillation columns deal with high and low-pressure units where low energy consumption results in efficient working of the column [70]. Constraints with these columns includes minimum pressure drop, minimum height of the column, safety environmental requirements. Bioprocessing applications include various technologies related to the final product such as marine processing, waste processing, food and beverages, agricultural processing, medical processing and textile processing [71]. Major flow incorporates the upstream product, transformation stage outcome and downstream product in these technologies. Constraints include most of the factors already discussed in the paper where conventional distillation will not be sufficient to meet the requirements. Moderations in control strategy and monitoring plays a vital role in working with bioprocessing applications. Additional separating agents helps in creating new bonds and formation of structures in the column during bioprocessing [72].

VII. Distillation column performance testing and trouble shooting

Performance testing incorporates the working of column parameters, capacity of the column, tray size, pressure drop, holding rate, mass transfer, efficiency, energy transfer, hydraulic and pneumatic design constraints, locations and configurations of columns. Health safety and environmental constraints are given highest priority in column working. Test systems include air/water usage, hydrocarbon usage, reflux heating problems, composition range and their physical properties has to be considered. Installation of column deals with vapor inlet, distributor and collector, packing, density and viscosity of the product under measurement [73]. Operations constraints include pressure, level, flow and temperature parameters in a column and measurements of these parameters are carried out with high tensile sensors and controlled with effective actuators. Column size and model plays a vital role in the performance and application of a column. Test conditions and testing procedures are incorporated for a distillation column with respect to the changes in efficiency and pressure drop. Testing also includes the loss in heat, variation in composition, steady state condition, instrumentation and sampling. Test objective and test sequence should be provided in a clear way for better understanding about the column working [74].

Trouble shooting of distillation column working deals with a defined strategy focusing on facts, theoretical and actual performance measures, past experiences, simplification of complex unit operations, human error interventions, reducing/avoiding hazardous malfunctions, maintaining proper documentation for future use [75]. Common column problems occur frequently are capacity related, efficiency related, deviations in process parameters, start-up/shut down issues, commissioning issues, instability issues. Rapid increase/decrease in flow may also cause heavy instability problems and also result in poor separation.

VIII. Conclusion

A brief discussion about the nonlinear distillation column process has been presented in this paper. It includes the adverse effects in the column, modelling of a distillation column, types of distillation columns with their working and applications. MIMO and SISO systems were presented for better understanding of the nonlinear process. Conventional controllers for a distillation column are discussed and necessary modifications for various applications has been reviewed. Optimization technique and fault tolerant control with reconfiguration is outlined in the paper which helps to find effective control setting of a distillation column. With the types and applications of distillation column are concerned, elaborate note has been provided along with case studies for better understanding. Finally, distillation column performance testing and troubleshooting measures helps in comfortable understanding and working with the nonlinear process.

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