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Assessing Safety in Distillation Column Using Dynamic Simulation and Failure Mode and Effect Analysis (FMEA)

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Abstract: Safety assessment becomes an important activity in chemical industries since the need to comply with general legal requirements in addition to meet safer plant and profit. This paper reviews some most frequently causes of distillation column malfunction. First, analysis of case histories will be discussed for providing guidelines in identifying potential trouble spots in distillation column. A dynamic simulation for operational failure is simulated as the basis for assessing the consequences. A case study will be used from a side stream distillation column to show the implementation of the concept. A framework for assessing safety in the column is proposed using Fault Mode and Effect Analysis (FMEA). Further, trouble-free operation in order to reduce the risk associated with column malfunction is described.

Key words: Safety assessment, distillation column, dynamic simulation, failure mode and effect analysis

INTRODUCTION

Safety assessment becomes an important activity in industrial sustainability since the need to comply with general legal requirements. Also, an unsafe plant cannot be profitable over a period of time and due to losses of production as well as capital. Therefore, the objectives of a safety analysis are (CCPS, 2000).

- Reveal weaknesses of the plant
- Identify and describe relevant sequences of events
- Quantify frequencies of releases related to their consequence-potential
- Investigate safety gains from various possible system modifications and
- Improve the system if necessary (either alone or in combination with others).

Accordingly, the framework for assessing safety is referred (Kister, 1997):

- Potential of flammable thermal of materials or mixtures under particular process.
- Trend of increasing temperature and/ or pressure at particular process and thermal production.
- Potentials of ignition and fire, either due to pressure, temperature, or concentration of processes.
- Toxic materials release.

Therefore, this paper will describe a tool for safety assessment in distillation column. First, some troublesome distillation columns are discussed. The discussion is based on Kister's malfunction report histories (Jimoh, 2004). Then, one cause of possible malfunction is selected for the case study of the simulation of plant disturbance. Eventually, t the effect of malfunction is described.

THEORETICAL BACKGROUND

Safety in distillation column: Distillation column is the most commonly applied separation processes used in chemical industries. From safety point of view, there are significant numbers of safety disturbances in recent years based on Kister's surveys on column malfunction histories (Kister, 2003). The hazards in distillation emerge from high material contents and equipment complexity. Based on this fact, it is important to detect all important effects for safety and integrate into process model. The most important effects that must be investigated in distillation column are (Can, 2004):

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- Influence of the hydrodynamic and mass transfer
- Control loop stability during nonstandard operation
- Effects of operational conditions on process safety
- Effectiveness of the protective systems

Dynamic simulation for safety analysis in distillation column: In order to systematically characterise the effect of different operational disturbances, the use of dynamic modelling of the column can be a powerful tool for safety assessment taking into account that the malfunction is considered as reducing the optimum condition. Detailed dynamic simulation of operational failure (i.e., column malfunction) gives information concerning internal process behaviour.

Therefore, the objectives of disturbance analysis are:

- Assessment of physical effects of disturbance in the plant
- Evaluation of possible malfunctions
- Technical know-how for relevant disturbances and associated effects, as well as risk on economy and emission
- Assessing alternatives for system optimization
- Assessing system protection

It is also the intention of further research in this field to attain the advantages on the dynamic simulation that the disturbance simulation can be integrated with the following objectives:

- Assessing the consequence
- Assessing the probability
- Measuring safety-related optimization for plant and processes

Risk assessment: Risk is defined as a measure of human injury, environmental damage, or economic loss in terms of both the incident likelihood and the magnitude of the injury, damage, or loss. Risk analysis involves the development of an overall estimation of risk by gathering and integrating information about scenarios, frequencies and consequences and it is one major component of the whole risk management process of a particular enterprise. In the process of risk analysis, both qualitative and quantitative techniques can be used, as shown in Fig. 1. In practice, risk is often viewed as the product of the probability of an incident times consequence of the incident, as formulated in equation.

$$\text{Risk} = f\,(s, c, f) \qquad (1)$$

where s, c and f stand for scenario, consequence and frequency, respectively.

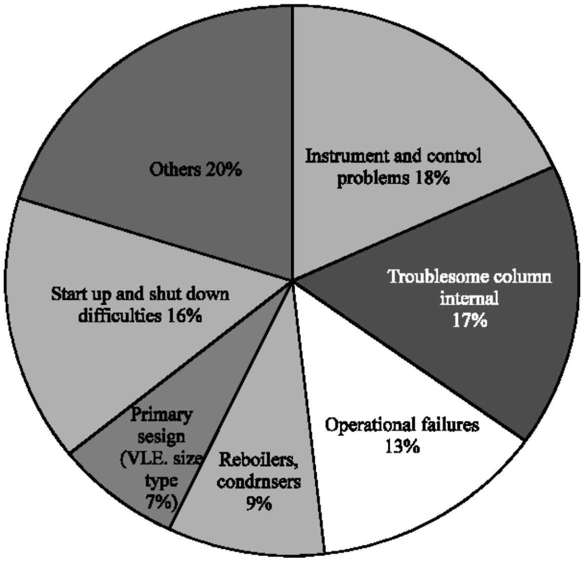


Fig. 1: A report on distillation malfunction histories (Jim, 2004)

A variety of techniques have been used for risk analysis in the chemical process industries including Safety Review, Checklist Analysis, Relative Ranking, What-if Analysis, Preliminary Hazard Analysis, Hazard and Operability Study (HAZOP), Failure Modes and Effects Analysis (FMEA), Fault Tree Analysis (FTA), Event Tree Analysis (ETA), Cause-Consequence Analysis (CCA), Human Reliability Analysis (HRA). Brief overviews of two methods will be discussed in the next paragraph, namely FMEA and ETA.

Failure Mode and Effects Analysis (FMEA): FMEA is a systematic procedure in which each equipment failure mode is examined to determine its effects on the system and classify it according to severity and criticality. FMEA is an inductive method oriented toward equipment rather than process parameters. All of the failure modes for each item of equipment are tabulated with their effects, safeguards and related actions listed. An FMEA is especially useful to identify single failure modes that lead to an incident directly.

Event Tree Analysis (ETA): An event tree is an inductive reasoning process that starts with an initiating event followed by the binary success or failure of subsequent safeguards, human responses and other safety measures to determine its possible outcomes. It is especially suitable to find possible outcomes of particular initial events and their respective probabilities with the data for initial events and subsequent protections and procedures.

Previous literature: Elaahi and Luben (1983) has modelled the concept of distillation column with pressure relief system and performed some experimental work on pressure relief systems. The description of pilot plant measurement techniques to validate the simulation work has been described. Then, the simulation work was verified by an experimental work to validate the simulation of pressure relief as well as the case when the disturbance took place. He described also the scenarios that leads to the disturbances to occur and mechanism of pressure relief system. A dynamic simulation of operational failures were also performed by Can (2004) using Promps for methanol-water system.

Can *et al.* (2002) described a safety assessment method using Failure Mode and Effect Analysis (FMEA) that is applied in distillation column. These methods are started from the formulation of the event tree and fault tree. The Event Tree Analyses (ETA) starts from a defined initiating event and identifies potential consequences in a systematic way, where as the Fault Tree Analysis (FTA) starts from a defined undesirable (consequence) event and identifies basic events (like component malfunctions, operator errors etc.) which may lead to this undesirable event. This FMEA method requires raw data regarding explanation of the system/equipment function, fault-effect analysis, valuation of weak point, weak point elimination and minimisation and risk potential minimisation.

Case study: The case study uses a column as a recycle part of nonseparated acetone from heavy ends column as shown in Fig. 2. Therefore, the separation task of this column is to separate valuable acetone into head column and the rest into the base column. The efficiency of separation is influenced by the available heat fed into column. In this case, live steam is fed from the base as the heat source.

The column feed stream is preheated in a heat exchanger by the hot base stream of the column and enter at tray 17. Live steam is injected into the base and the steam flow rate is temperature control at stage 27. The column has 35 valve trays. The head product is condensed in a heat exchanger with the vent passing through another heat exchanger to the atmosphere and the liquids are collected by reflux drum. The reflux is transferred under flow control back into the column on stage 35. The crude acetone is pumped through a heat exchanger for cooling under level control and on to acetone recovery plant. The base product passes the heat exchanger and runs on through another heat exchanger for further cooling and is then discharged into the in-plant effluent pit.

The column side stream is equipped in order to attain more middle boiling component, methanol and decrease its adverse effect in the base stream. Such side stream configuration is also suggested consuming less energy (Alatiqi and Luyben, 1985; Elaahi and Luyben, 1983). The composition of feed stream is shown in the Table 1 and the coupled variables between process variable and output variables are shown in Table 2.

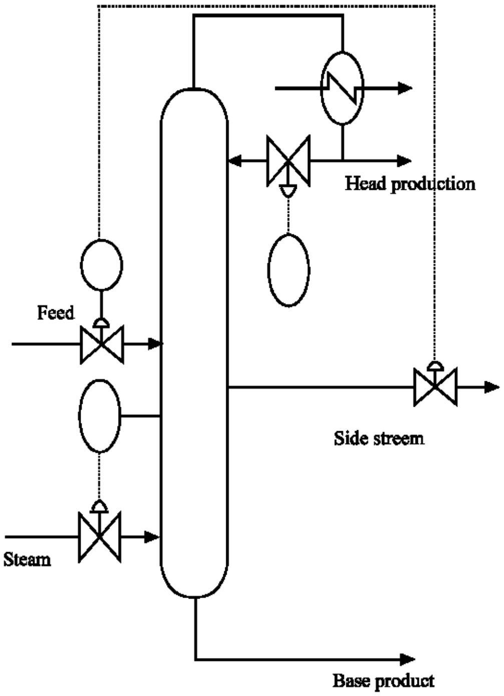


Fig. 2: Distillation column configuration for the case study

Table 1: Feed composition

Component	Composition (mass %)
Acetaldehyde	2.212
Acetic acid	1.752
Acetone	13.111
Diethyl ketone	0.098
Ethyl acetate	0.246
Ethanol	1.060
Formic acid	0.370
Methyl acetate	2.344
Methyl formate	3.770
Methyl ethyl ketone	0.565
Methanol	1.652
Propionic acid	0.136
Water	72.682

Proposed safety assessment: The assessment of risk potential refers to following framework:

- Consequence assessment with support of tabulated method and/or disturbance simulation.
- Consequence assessment with support of initiating events methods.
- The use of risk potential matrix for defining of not acceptable risks.

- The application of disturbance simulation for recognition of
- The optimal plant
- The optimised process
- The alternative/ renewed consequence of weak points
- Optimisation of the plant and/ or process through technical as well as organisation at framework.

The framework originates from the definition of initiating event, top event and the probability as well as the consequence. These are assessed and listed in a Table 2 and 3. The consequence addresses the intensity of side effect from particular system (e.g., effect to the environment). The general criteria of consequence are expressed qualitatively from very good implying that the improvement is not urgent to be applied, until bad condition of the system. The valuation and the description of consequence is shown in Table 1. Whereas, the valuation the probability is started from 1 (very low, probability = 10^{-7}/year) and ended with 9 (very high, probability = 10/Year), as shown in Table 4. Then, the combination of probability and consequence value results in the Risk Potential Index (RPI) which has significant meaning for the priority of improvement of a definite plant that can be plotted in RPI matrix. There are 3 regions in RPI matrix, acceptable regions, not acceptable region and acceptable region but with further evaluation or optimisation. The development of RPI matrix will be shown later.

Table 2: Coupled variables pairings for the case study

No	Controller	Process variable	Output variable
1	Pressure Control	Pressure on Stage 1	Cooling Water Flowrate
2	Condenser Level Controller	Liquid Level on Stage 1	Distillate Flow rate
3	Reflux/Head Controller	Temperature at Stage 4	Liquid Head Flowrate
4	Steam Controller	Temperature at Stage 20	Steam Flowrate
5	Sidestream Controller	Sidestream flowrate	Feed flowrate
6	Sump Level Controller	Sump Level	Bottom Flowrate

Table 3: Valuation of consequence

Consequence Value	Description
1-3	Good
4-5	Satisfied
6-9	Bad

Table 4: Valuation of probability

PV*	Frequency	Probability
1	10^{-7}/Year	Very low/ implausible
2	10^{-6}/Year	Low
3	10^{-5}/Year	
4	10^{-4}/Year	Moderate
5	10^{-3}/Year	
6	10^{-2}/Year	High
7	10^{-1}/Year	
8	1/Year	Very high
9	10/Year	

*PV: Probability Value

DISCUSSIONS

Dynamic simulation results: The dynamic simulation is performed using ASPEN Dynamic. The running time is 20 h. After 1 hour steady state operation, the cooling water is reduced to 10%. This disturbance leads to a pressure increase in the column. Reducing cooling water supply will cause a substantial reduction of the condensation rate. According to the condenser duty equation:

$$Q_{cond} = \dot{m} \bullet C_p \, \Delta\vartheta_c = k \bullet A \bullet \, A \, \Delta\vartheta_m \qquad (2)$$

Therefore, at the constant heat supply to the column, reducing cooling medium will lead to increasing the temperature different. Then, an accumulation of vapour in the condenser will occur, causing pressure increase (Fig. 3).

Decreasing of cooling water leads to increasing pressure in the column, then temperatures of every stages will increase accordingly. The increased pressure and temperature in the column will lead to a partial condensation of the vapor phase at the constant of heat input. This leads to increasing temperature at head and base stages (Fig. 4). One possible consequence due to cooling water reduction is poor product quality (Fig. 5).

Assessing safety: From safety point of view, increasing base level will give potential hazard due to increasing risk

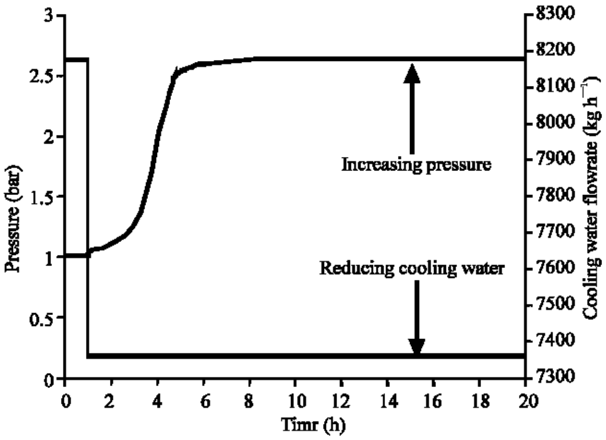


Fig. 3: Profile of increasing pressure after cooling water reduction

on malfunction. It is true since most of Kister's malfunction histories emanate from bottom level failure due to the problems of excessive liquid raising.

According to Kister (2003) bottom problems cause 50% of the problems in distillation column. Therefore, potential liquid level rising above the base return inlet or bottom gas feed must be identified. Then, tower base level can be avoided. The potential consequence of problems on base tower are tower flooding, poor separation, instability and less vapour slugging through the liquid. All these problems can cause physical damage and threat to safety, as shown in Table 5. The values of semi-quantitative associated consequence are also given.

The prevention action for trouble free operation of distillation column in order to avoid those problems are reliable level monitoring, redundant system and good sump design (Kister, 1997). In addition, the issue on control assembly difficulties must be solved. The key success for this problems are a suitable control tray and pressure compensation for temperature control (Kister, 2003).

The event tree for cooling water reduction is developed as shown in (Fig. 6 and 7). And according to Table 4 and 5 above, the value of probability and consequence are determined. All values for possible risk are tabulated in the Fig. 8. A matrix of risk potential indices are created. Then the value of each risk potential index due to cooling water reduction can be defined. The values for all risk of consequence occurrences are 1, 7, 30, 28, 28, 30, 35 and 21, respectively. The darker the area in the matrix is, the higher risk will be. The information of potential risk is then documented in the FMEA data base. According to Fig. 6, all possible different operational

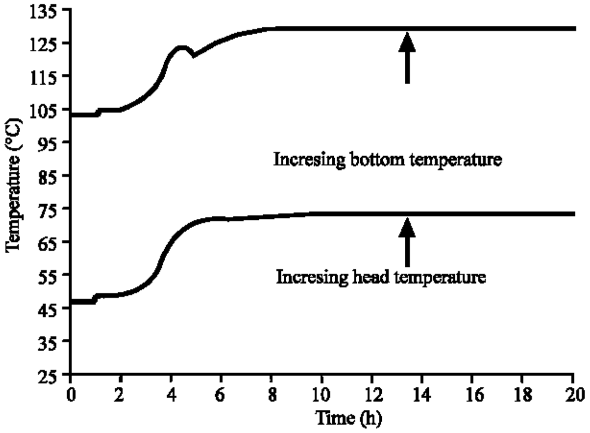


Fig. 4: Profile of increasing head and bottom temperatures after cooling water reduction

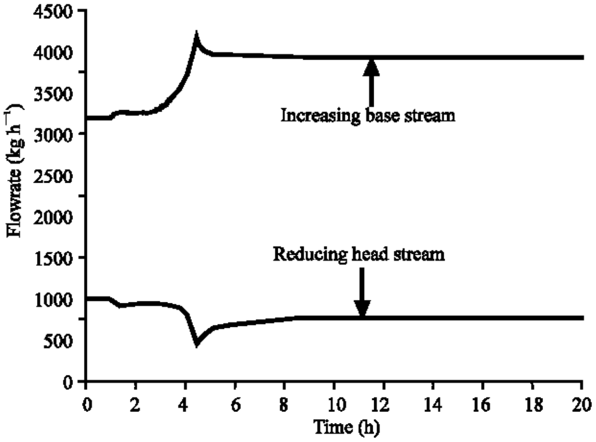


Fig. 5: Profile of increasing base stream and decreasing head stream after cooling water reduction

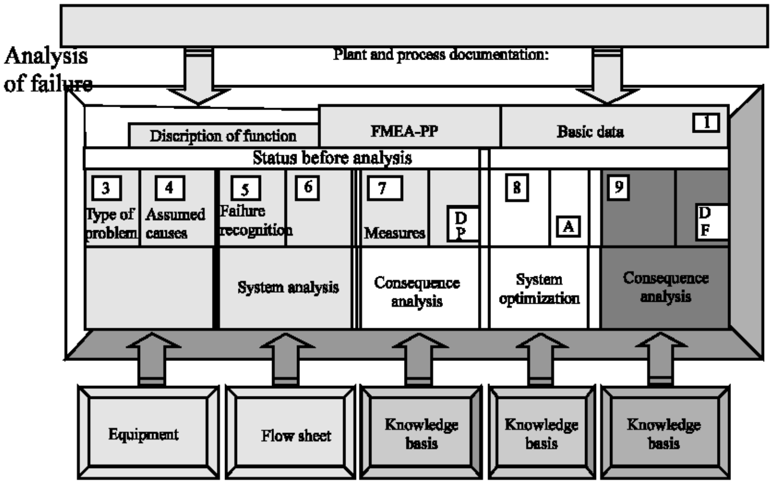


Fig. 6. FMEA data base for plant and process

Table 5: The valuation of associated consequence for cooling water reduction

CV*	Type of Failure	Technical Example	Production Example
9	Safety and	Explosion	
8	environmental	Bursting of the column	
7	impact	Fire with destruction	
6		Fire (Pump/Heat exchanger/Boiler) with destruction	
		Emission through pressure release	
			Product interruption (long time)
5		Bottom failure (Flooding)	
	Mal function	Pumping failure	
		Reboiler failure	
		Material release due to leak	
			Product interruption
4		Emission through pressure relieve	
		Bottom Failure	
			Production interruption (short-time)
3	Function		Decreasing product quality (long-time)
2	disturbance		Decreasing product quality
1			Production interruption (short-time)

*CV: Consequence value

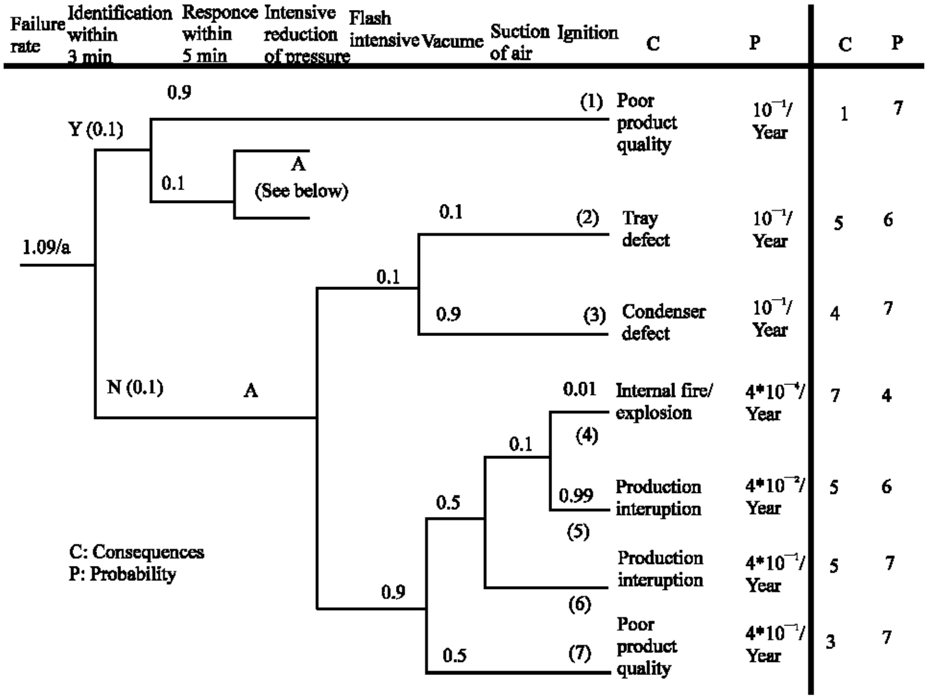
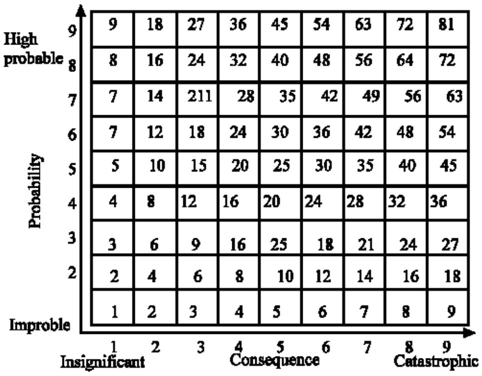


Fig. 7: Event tree for cooling water reduction. The number in the bracket represents the consequence



	1	2	3	4	5	6	7	8	9
9	9	18	27	36	45	54	63	72	81
8	8	16	24	32	40	48	56	64	72
7	7	14	211	28	35	42	49	56	63
6	7	12	18	24	30	36	42	48	54
5	5	10	15	20	25	30	35	40	45
4	4	8	12	16	20	24	28	32	36
3	3	6	9	16	25	18	21	24	27
2	2	4	6	8	10	12	14	16	18
	1	2	3	4	5	6	7	8	9

Fig. 8: A Matrix of Risk Potential Index

failures will be included in FMEA data base. With the aid of this data base, risks can be assessed for normal operational states as well as in case of operational failures.

CONCLUSIONS

The focus on recent assessment methods in distillation column is to identify the trends and to flag major regions of growing malfunction. The lessons from malfunction histories as well as simulation of column malfunction can save engineers and operators from failing into the same trap.

Using dynamic modeling of the column behavior during operational disturbances, the effect of such disturbances can be systematically characterized. The results could then be used for decision making in the development of new design regulations that would help to achieve hazard free operation or at least help in identifying the hazard potential of column under safety consideration.

Further combined analysis of the dynamic column behavior during non-standard operation together with the safety assessment method (such as FMEA) should give a deeper understanding of system safety. In addition, an assessment method for column safety should be integrated in an automatic way for thorough analysis of safety in distillation column.

Nomenclature:

A : Condenser area (m^2)
Cp : Heat capacity (kJ/kg.k)
k : Heat transfer coefficient ($W/m^2 . K$)
$\dot{m}$: Cooling medium mass rate (kg h^{-1})
$\Delta\vartheta_c$: Temperature difference of cooling water (K)
$\Delta\vartheta_c$: Log mean temperature difference [K]
Q_{cond} : Condenser duty (kW)

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