Technical Analysis of Accident in Chemical Process Industry and Lessons Learnt

Kamarizan Kidam[1,2], Markku Hurme[1], Mimi H. Hassim[1,2]
[1]Helsinki University of Technology, Plant Design, Department of Biotechnology and Chemical Technology, P.O. Box 6100, FIN-02015 TKK, Finland
[2]Universiti Teknologi Malaysia, FKKKSA, 81310 UTM Skudai, Johor, Malaysia

A study of past accidents in the chemical process industry (CPI) has been carried out. It is found that the majority (73%) of the accidents were caused by technical and engineering failures. Based on the causes of accident and types of equipment failures, five common features of accident in the CPI were identified. The analysis reveals that the contribution of the design to accidents is significant and the advancement of knowledge/technology is not shared effectively by practitioners. Dependency on the add-on control strategy should be reduced and inherently safer or passive engineered must be considered as premier risk reduction strategy to lessen the safety load, for better design and to prevent accident effectively.

1. Introduction And Research Approach

Analyzing the past accident cases is very important for continuous improvement of process safety. It gives useful information on how accidents arise in practice. There are many studies related to accidents have been carried out worldwide and majority of them concentrate on identifying the root causes of accident and lesson learnt from it. Most of them classified causes of accident into the technical/physical and human/organizational failures. The contribution of the organizational/human aspect to accident is well discussed and accepted by the CPI. However, analysis on the technical aspect of the accident is still lacking. This may relate to the quality issue of accident reports. Majority of the accident reports are not complete or poorly written due to inadequate investigation and competency (Kletz, 2009). To minimize this issue, the Failure Knowledge Database (JST, 2009) was selected. The database covers the most significant accidents all over the world and is managed by experienced academia from Japan under close monitoring of Japan & Science Technology (JST) Agency. The accident report is carefully reviewed by the nominated committee and contains almost complete information of the accident. Some of them contain detailed technical drawing, process flow diagram, plant layout, fault tree analysis, and proper comment on the background of the accident.

In this paper, 364 accident cases related to the CPI are analysed based on the technical and engineering aspects of the chemical plant failures. The basis of the statistical analyses is based on the causes of accident, equipment failure, and operational status.

The information available in this accident database enables to draw learning from the accidents via technical/engineering perspective for better design and safe plant operations.

2. Results and Discussion

This section discusses the statistical analysis of accident involving 364 cases in Failure Knowledge Database covering causes of accident (technical and organizational factors), types of equipment failure and operational status. The results obtained from this analysis will be used to develop the common features of accident from technical and engineering point of view.

2.1 Causes of accident

Figure 1 shows the general (pie chart) and immediate (bar chart) causes of accidents in CPI based on Failure Knowledge Database. It clearly indicates that majority of the accidents are caused by technical failures (73%), followed by organizational (23%) and unknown (4%). In this work, special attention on 'human engineering error' is given for the accidents caused by human failures by asking questions such as *"why did the operator make a mistake"; "why the operator did not follow the instruction/ procedure"; "why the operator repeat the same mistake"* etc. As a result, majority of the human errors (under management/procedural category) are shifted to technical causes due to design error of work unit. Among typical examples related to the 'human engineering error' include wrong equipment/component labeling, confusing control panel display, wrong work instruction and standard operating procedure, wrong color-coding, and poor visibility and accessibility to the equipment.

2.1.1 Technical causes

The bar chart from Figure 1 shows the root causes of accidents in CPI. The most frequent cause of accidents in the Failure Knowledge Database are the *piping system* failures (16% from 364 cases). Accidents related to the piping systems involved loss of containments or leakages that leads to toxic dispersion, fire and explosion. From the analysis, typical problems associated with the piping system are poor layout, wrong specification, dead end or no flow arrangement, poor installation and finishing work, inadequate hot bolting, and blockage. Technically, the piping system is complex due to multiple interactions between process equipment. The demand for higher process flexibility increases the complexity of the system. The likelihood of the piping failure is a function of failure rate of its components. If the number of the components increases, the probability of the system failure will increase. Thus, designing a simpler piping system is the best way to prevent accidents in the CPI.

The second largest cause of accidents is *contamination* of the process stream with 36 cases (10%). In this category, impurities, by-product and in-direct or external contaminations are also considered. The basic problem of the contaminations is related to insufficient process hazard analysis at the process development and plant design. Contaminations also occur due to incomplete draining/cleaning/purging, reverse flow, pressure difference, blockage, leakages and condensation due to weather changes. In chemistry term, the contaminant changes the quality of process stream and creates a lot of operational problems such as increase the corrosion rate, partial/full flow blockage, wall sticking, depositing or scaling, disturbed/delayed chemical reactions, etc. If unstable or reactive material presents and the conditions are right (i.e. temperature and concentration), an unwanted reaction (i.e. polymerisation and decomposition) may occur, resulting unwanted events such as fire and explosion.

Inappropriate selection of *construction material* (29 cases or 8%) is the third contributor of accidents in CPI. This is a design related error and normally connected to the physical and mechanical problems of process equipment such as cracking, corrosion, erosion, creep, fatigue and shock. For example, selecting mechanically robust construction material as well increasing the wall thickness of process equipment can eliminate wall failures. Meanwhile selecting a chemically resistant construction material such as stainless steel or teflon can minimise the corrosion issue.

The contribution of *mass transfer* and corrosion/erosion are also significant (26 cases or 7% each). Accidents resulting from poor or no mixing, excessive charging, and varied feed conditions are common factors related to the mass transfer category and consequently lead to uncontrolled reactions. Meanwhile, *corrosion/erosion* may be resulted following operational scenarios, such as flow restriction, process condition deviations, and raw material variation. Among the factors that accelerate corrosion rates are changes in process conditions i.e. higher temperature and pressure, high pH value, and contaminations by specific materials from other process streams or from outside.

Heat transfer is also a very usual contributor of chemical plant accidents, causing 20 accidents. Loss of cooling, wrong heating method, hot spots, and scaling in the piping system and process equipment are among the problems associated with heat transfer-related accidents. Special attention should be given to thermal expansion phenomena and the reactivity hazard of heat transfer media to the process fluid.

The low fraction of accident causes should also be noted i.e. *substandard equipment* (5%), *fabrication* (4%), *flow related* (4%), *layout* (3%), and *control system* (2%). Still, even the small percentage cause, may generate big problems if not managed properly.

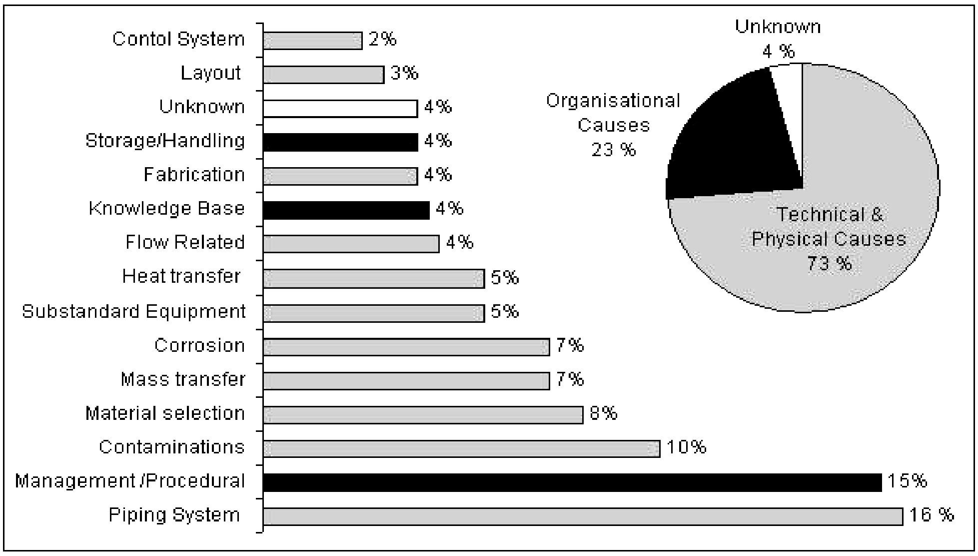

Figure1: The general (pie chart) and immediate (bar chart) causes of accident.

2.1.2 Organizational causes

Out of the 364 accidents analyzed, 23% are classified as organizational causes which is categorized as management/procedural faults (15%), knowledge-based (4%) and storage/handling of chemicals (4%) Almost all of the organizational failures are causes by poor human performance. Majority of the faults are caused by the managerial level due to wrong policies/directions, inadequate hazard recognition, wrong/inadequate instructions, as well as personal factors e.g. incompetence and risk taking. At the operator's level, the main factors that contribute to accidents are mistakes, short cut, not following instructions, miss-judgement, and under estimation chemical safety.

The contribution of knowledge based and chemical handling related accidents are also explored. It is found that the basic reason for knowledge-based accident is due to ignorance of technology advancement and knowledge sharing (Kletz, 1993). Many organizations do not update their operations to the current code of practice based on technical guidelines as provided by the authorities. For the chemical handling related accidents, the majority of the accidents are classified under wrong valve setting, operator doing "short-cut" and not following work instructions.

2.2 Equipment failure

Based on the information available in 364 accident reports, the frequency of the equipment failures are examined and classified into 12 main categories. The resulting categories of equipment failures and their respective percentage are: piping (25%), reactors (15%), storage tanks (14%), process vessel (10%), heat exchanger (8%), separator (7%), general machinery (5%), other equipment (5%), drum (4%), warehouse (3%), control system (3%), and cylinder (2%).

The result shows that piping is the most fragile component of chemical plant operations. In general, piping failures are caused by design error (i.e. unsuitable construction material); corrosion and erosion issues; poor operations and project implementation (i.e. fabrication/ installation). They can be eliminated or minimized by proper design and operation within safety limits. Meanwhile, reactor is the heart of chemical processes and has a risky task. Chemical contaminations are the common contributing factor associated with reactor failures. Abnormal reactor operations also caused by uncontrolled mass transfer phenomena (i.e. poor mixing, more reactant, and diffusion issues); flow related problems, and heat transfer issues. These problems increase the risk of unwanted chemical reaction in the reactor that result to toxic release, fire and explosion. Storage tanks should be safer equipment if compared to others but statistically the accident rates are high. Operational problems associated with the storage tanks are related to poor management practice (i.e. hot work and confined space entry) and improper operations (contamination, heating, and static electricity).

Similar results have been published by Marsh & McLennan Inc. (1987). It is interesting to notice that the CPI has been aware of these facts for more than 20 years but the same types of equipment failures still occur. The reason for this may be due to lack of technical analysis, wrong interpretation of the evidence and inadequate knowledge sharing (Kletz, 1993; 2003). On inherent safety point of view, it seem that the current control strategy used by the CPI, i.e. add-on control systems are ineffective to prevent accidents. Logically, the add-on systems may fail and their reliability reduces if not properly maintained.

2.3 Operational status

Based on Failure Knowledge Database, the operational status of the equipment failures is also studied. 49% of the accidents occur during normal operations (178 out of 364 cases), followed by charging/chemical transfer (18% or 66 cases) and maintenance work (12% or 42 cases). Other operational status with their respective percentage are cleaning activity (7%), start up (4%), inspection/testing (4%), emergency (4%), environmental factor (1%), and shutdown (1%). Half of the accidents occur during normal daily operations and occur without any sign, such as piping failure due to corrosion and runaway reaction due to chemical contamination. Briefly, plant owner/operators were not aware what went wrong, resulting panic situation. This sometime worsened the consequences of accident. Based on the accident reports, the basis of the equipment failure and the root cause of the accidents are related to design error, which only appeared after an accident. Accidents related to chemical handling, maintenance and cleaning work are significant and directly caused by poor management of plant operations. Meanwhile, the analysis shows that the plant start-up is more risky if compared to the plant shutdown. However, both activities require good planning and technical knowledge.

3. Common Features Of Accident And Lessons Learned

From the accident cases reported in Failure Knowledge Database, a number of similarities appear. These can be summarized as following:

- Majority of the accidents are caused by *failure of auxiliary systems* and its components, not the main equipment. Typical example is piping system. The integrity and reliability of the piping system depend on many factors including design, complexity and management. The integrity and reliability of the piping system can be achieved by selecting robust material of construction and through simpler design. Well-structured pipes inspection and replacement is a good element of piping management system.
- Almost half of accidents occur during normal operations and are directly related to the *design error*. Typical examples of design error in the CPI are unsuitable construction material for equipment, incorrect design capacity and design rating/specification, poor layout, and physical arrangements. Proper process analysis is needed especially on identification of inherent physical and chemical properties of substances; stability and incompatibility of process fluids with construction material; and runaway reaction hazards. In addition, detail risk analysis based on worst-case scenario should be conducted and the result should be used to design the equipment’s protective and mitigation system.
- Lack of process analysis in respect to *chemical reactivity and incompatibility*. Identification of hazards associated with reactive materials and the potential of the process contamination as well as material accumulation in process stream should be made known as early as possible, i.e. in research and development stage. The data can be used as criteria for raw material selection during process screening or process concept development. Selection of safer, stable and compatible raw material can eliminate or reduce the overall risk of the chemical process plant operations.

- Operational fault as a result of *operating beyond the equipment design limits*. The real issue here is the record keeping and technological updates. Some of the companies did not maintain the original technical specification of the process equipment or update the current technology/chemistry knowledge of the process employed. These situations lead to use of sub-standard or unsuitable equipment in normal operation. Similar issue is related to the management of change especially on plant modifications.
- Under estimating the problem related to *thermal expansion phenomena*. Many of the heat exchanger and piping system failed due to these phenomena. The origin of the problems is somehow related to design error and poor plant operations such as material miss-match, uneven tightening and support arrangements. Mechanically, metals expand at different rate and create gap between them. For the high temperature services, hot bolting and heating/cooling rate are very important for this issue. Special considerations on piping movement are also required during structural or support installation of major equipment.

4. Conclusion

Based on the accident report in the Failure Knowledge Database, the technical and engineering aspects of plant operation are found to be important causes of accident in the CPI. 73% of accident cases were caused by technical and engineering failures. Furthermore, the study found five common features of accidents, which are related to the auxiliary equipment, design error, chemical reactivity and incompatibility, operational fault, and thermal expansion issues. It is evident that the contribution of design to the accidents is significant and current knowledge of science and technology in the CPI is not shared and used effectively to combat design and operational error. Effort to share the latest knowledge and technology should be enhanced for healthy plant design and operation. In general, the result of the analysis point out that the add-on control strategy is inefficient to prevent accidents. As a control systems are subject to failures, the dependency on add-on control systems should be reduced. To increase the reliability and availability of the chemical process plant, the inherently safer approach should be considered as a premier strategy for risk reductions in the CPI.

References

JST, 2009, Failure Knowledge Database, Japan & Science Technology Agency, Japan. http://shippai.jst.go.jp/en/Search, Online available on 29th October 2009.

Kletz, T. A., 1993, Lessons from Disaster: How Organizations Have No Memory and Accidents Recur. IChemE, Rugby.

Kletz, T. A., 2003, Still Going Wrong! Case Histories of Process Plant Disasters and How They Could Have Been Avoided, Gulf– Butterworth Heinemann, Burlington.

Kletz, T. A., 2009, Accident reports may not tell us everything we need to know, Journal of Loss Prevention. in the Proc. Ind., doi: 10.1016/j.jlp.2009.08.017

Marsh Inc., 1987, A Thirty-Year Review Of One Hundred Of The Largest Property Damage Losses In The Hydrocarbon-Chemical Industries. Marsh Inc., New York.