PROCESS INTENSIFICATION: SAFETY PROS AND CONS

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One of the best ways of preventing accidents is to avoid hazards by inherently safer design. The adoption of such principles is now required by EU legislation. As many processes, particularly those in the chemicals, nuclear and oil industries, involve the production, handling and use of hazardous substances, process intensification (PI) is one way in which the inventory of such substances, and the consequences of a process failure, may be significantly reduced. PI, therefore, has the potential to be a significant factor in the implementation of inherent safety. However, conflict can arise between PI and some inherent safety practices. For example, certain PI technologies require higher energy inputs or to be operated at higher temperatures. The processes may be more complex or call for a more complex control system. For this reason, both the process (including the chemistry, where appropriate) and plant need to be considered together to reach a comprehensive understanding of the safety issues. This paper gives some examples of how process intensification has, or might have, improved safety. Some of the issues that need to be considered are also discussed. In order to promote the benefits of process intensification, and draw attention to safety considerations, HSE is co-sponsoring a process intensification network (PIN) in liaison with industry and the Department of Trade and Industry.

INTRODUCTION

As all good safety professionals know, the best way of preventing accidents is to avoid hazards by inherently safer design. The adoption of such principles is currently required by EU legislation (for example references 1 and 2). Many processes, particularly those in the chemicals, nuclear and oil industries, involve the production, handling and use of large quantities of hazardous substances and process intensification (PI) is one way in which the inventory of such dangerous substances, and the consequences of a process failure, may be significantly reduced. There are also a number of business reasons for the uptake of PI, such as the possibility of producing new or better products and the ability to have smaller, local production plants rather than a large central one. The environment may also benefit. Consequently, there is much interest in its uptake and a number of companies and academic institutions are developing new intensified processes with the aim of them being, ultimately, adopted by the industry. However, in some cases, hazards may remain or new ones may be created in the development of such processes. This paper discusses the potential for PI to improve process safety, and some of the possible drawbacks, which should be considered in the light of the legal framework.

LEGISLATION

The principal health and safety legislation in the UK is the Health and Safety at Work etc. Act 1974[3]. It requires employers to reduce risks to employees, and others, "so far as is reasonably practicable" (SFAIRP). The meaning of SFAIRP has been the subject of legal judgement in the UK Courts[4], but essentially the risks have to be weighed against the costs (in terms of time, trouble and money) necessary to avoid them. The more recent term ALARP (as low as reasonably practicable) has a similar definition. Measures to reduce risk should only be ruled out if the sacrifice involved is grossly disproportionate to the benefits.

The requirement to assess risks is also embodied in a number of Regulations, which implement European Directives on health and safety matters. In particular, The Management of Health and Safety at Work Regulations 1999[5,6] implement the EC Framework Directive[1]. These regulations require assessment of the risks created by work activities and the provision of suitable and sufficient measures to control them. Regulation 4 includes specific requirements to avoid risks by inherently safer design.

More recently, the European Chemical Agents Directive[2] (CAD) applies to all work places (including Universities) handling dangerous substances. In Britain, the safety aspects of CAD are enforced through the Dangerous Substances and Explosive Atmospheres Regulations 2002[9,10]. These specify that employers must:

- Carry out a risk assessment of any work activities (including processes) involving dangerous substances;
- Provide the necessary measures to eliminate or reduce the risks SFAIRP;
- Provide equipment and procedures to deal with emergencies;
- Provide information and training to employees;

It is a requirement of the risk assessment that the risk from hazardous chemicals is either eliminated or reduced to a minimum. By preference, hazardous chemicals or processes should be replaced by less hazardous options. The onus is clearly upon the employer to consider process hazards and avoid them, right from the earliest stages in the process development. It is only once this has been done that companies should move on to further "add on" safety measures to either avoid or control these hazards.

This has profound implications for both the process industry and researchers involved in developing new processes. However, the Chemical Agents Directive only exemplifies what has always been good safety practice. Politicians and the public alike are becoming increasingly aware of the hazards posed by industrial chemicals and are increasingly questioning whether safer options are available[9,10].

PROCESS INTENSIFICATION — SAFETY BENEFITS

The safety advantages of process intensification are best expressed by Professor Trevor Kletz[11]who put it quite simply saying, "What you don't have, can't leak!" For hazardous processes, PI is one way that the inventory of such dangerous substances, and the consequences of a process failure, may be significantly reduced.

As an example[12], consider the worst-ever industrial disaster: The Bhopal Gas Tragedy. On 2 December 1984, 41 tonnes of highly toxic methyl isocyanate (MIC) leaked out of a ruptured storage tank at the Union Carbide pesticide manufacturing plant in Bhopal. Safety equipment had not been maintained. Over 3,000 died and over 200,000 were left disabled for the rest of their lives. Some adverse genetic mutations were also passed on to the next generation. The reaction scheme in this batch plant produced MIC as an intermediate that was stored until a decision was made to produce another batch of the product. If a smaller continuous reactor could have been used instead of the batch one, it would have produced only a few kilograms of MIC that would have been internally consumed during the final stages of the process, leaving nothing to store. Even if this reactor had ruptured, only a few kilograms of MIC would have been released which, comparatively, would have done much less damage. This is the application of one of the main concepts of inherently safer design: *use less of* hazardous substances.

Further safety benefits may arise from PI, for example:

- In some cases the number of process operations can be reduced, leading to fewer transfer operations and less pipework (which can be a source of leaks).
- It may be easier to design a smaller vessel to contain the maximum pressure of any credible explosion, so that further protective devices such as emergency relief systems, are not needed (or the duties placed upon them are less onerous).
- Many incidents are associated with process transients such as start-up and shutdown. These are reduced during continuous (and intensified) processes.
- For exothermic reactions, the heat evolution should be much less variable than in batch reactions, and should be easier to control. Furthermore the enhanced specific surface area of intensified plant makes heat transfer easier. Certainly, very few runaway reactions occur in continuous processes (although there have been some notable exceptions[13]).

In the UK, the HSE have been involved in encouraging companies to adopt more inherently safe designs. An example where PI was used to considerably enhance the safety of a process is given below.

Case Study 1: A company was manufacturing an energetic material in tonnage quantities. The final stage was a batch evaporation stage. As the material became more concentrated, it became possible for it to detonate. Potential mechanisms for initiation were by overheating or by iron contamination. A number of precautions had been taken to prevent this occurring. However, because the vessel was constructed of mild steel with a glass lining, there was a danger that the glass lining might be breached during the evaporation stage and the mild steel come into contact with the energetic material. Part of the company's basis of safety was that, if this occurred, the breach would be detected, steam to the jacket would be shut off, cooling water applied, and the material dumped through the discharge pipe at the base. However, the company were unable to demonstrate to

HSE that the safety system could work quickly enough before the vessel over-pressurized. The process was discontinued and replaced by a continuous wiped-film evaporator with only a few kilos of instantaneous inventory. Compatible process materials were selected and the process was operated remotely.

Other examples of the significant safety benefits of PI abound in the literature, for example references 11 and 14.

POTENTIAL PROBLEMS

Even though safety can benefit from process intensification, it is unlikely to be the main driver in most cases. Uptake will be based upon other factors such as reduced capital costs and better products. In some cases PI will allow new or better products to be produced commercially. In the drive towards newer processes, companies should be careful to ensure that new hazards are not created. Potential problems may include:

- Some PI technologies require high-energy inputs, e.g. from microwaves, high voltages or electro-magnetic radiation, or require to be operated at higher temperatures and pressures. Although expertise associated with the handling of high-energy sources is present in some industries, the new technology may also bring less familiar groups into contact with this hazard.
- The high-energy sources may introduce new hazards that have to be considered when applied to hazardous substances, e.g. whether or not it is safe to use microwaves on thermally unstable substances or mixtures.
- The processes may be more complex or call for more complex control systems and safety may suffer. An example is given in reference 14 which cites a chemical reaction where the reaction mass became dangerously unstable if one of the reactants was overcharged — the process was simpler to control safely by charging the reactant into an excess of the other in a semi-batch reactor. However, the author also makes the point that this needs to be balanced against the safety advantages of moving to a smaller inventory in the intensified process.
- As the residence time for many intensified processes will be in the order of seconds rather than hours, the subject of control and monitoring has to be addressed. It has been suggested that process control may become easier but more importantly, as the system is smaller, it becomes more responsive to changes in process conditions. Where it is possible that safety may be compromised as a result, then these issues should be addressed before the process is implemented. In some cases, it may mean that the process is unsuitable, or that new and novel techniques are needed to control them that may not yet be available.
- In some cases, process pipework may be more complex with a higher potential for equipment failure or operator error.
- Intensified reactors have the potential to significantly enhance reaction rates as a result of the improved mixing. This could lead to a much greater rate of energy release than

in traditional reactors and, in some cases, may result in a change in the reaction chemistry. This could have significant safety implications, unless the reaction has been adequately assessed first, for example if the enhanced reaction generates a gas rather than a liquid. Whilst time-proven techniques and procedures are available for assessing the likely reaction thermo-chemistry in traditional reactors, this is less evident for some of the new designs of intensified equipment.

- Rotating equipment may not be suitable for friction sensitive substances (i.e. substances that can either deflagrate or detonate due to friction). Certainly the hazard of ignition needs to be addressed.
- Where fouling can occur on complex heated surfaces, then thermally unstable materials can overheat, possibly leading to high pressures being generated.
- Although the instantaneous inventory can be quite low, the throughput may be quite high. It is important to consider the possibility of "off spec" products being transferred and accumulating rapidly downstream. Where necessary, suitable analysis and control measures will be required.
- Unlike the case with many large processes, people may be closer to smaller plant, particularly during the development stages.

In some cases these conflicts may be less real than they initially appear to be. This is sometimes the case for fast reactions, which can be more amenable to reactor process intensification than slow ones. Chemical companies used to conventional stirred tanks, may consider enhanced exothermic reactions as more dangerous from a conventional plant point of view. However, a well-designed intensified process should result in less accumulation of unreacted materials, and heat transfer should be easier. Many researchers also point out that, generally, intensified reactions require more detailed knowledge of the thermochemistry than batch reactions to operate efficiently, which should improve safety. *But* the hazards (including the reaction thermochemistry) need to be assessed first, *before* the reaction is used to produce significant quantities of product. This includes the development stages, where less may be known about the reaction and its sensitivity to process changes, and where researchers may come into close contact with equipment.

Where insufficient data is available, such as during these early stages, companies and researchers may have to assume that the worst can happen, and carry out the process in a protected environment — like the blast proof cells routinely used by reaction hazard assessors to carry out assessments of traditional processes.

It is worth adding that problems do not only occur when a reaction runs faster than anticipated:

> "An organization was in the early stages of developing an intensified process. Their initial trials in the laboratory were unsuccessful and only a 20% yield was achieved. Although the laboratory equipment was small, they discharged several tens of litres of unreacted materials into a downstream vessel that was not designed to contain the reaction, resulting in an uncontained runaway in the downstream vessel".

DISTRIBUTED MANUFACTURE

Another outcome of reducing the size of plant is that processing can take place at a local level with vast chemical complexes making way for ‘licensed microplants’ operating in, for example, the home, shop, community, or at the local supplier. This concept of “distributed manufacture” will, in many cases, allow the supply chain to be shortened with substantial cost savings. It may also remove the need for the storage of extremely large quantities of hazardous substances with their potential for major accidents. In some cases, the transport of hazardous materials may be avoided by manufacturing them at the user site.

Kletz[11] cites the example of cyanogen chloride that, at one time, was manufactured at one site and transported several hundred miles in cylinders. A hundred journeys were made per year. The process was intensified so that it could be made near to the point of use, and the inventory was reduced from 20 Te under pressure to a few kilograms at atmospheric pressure. Similarly the need to transport ammonium nitrate-fuel oil explosives (ANFO) to quarries and to store it on site can be avoided by making it at the point of use. However, this is not a safety benefit if the feedstocks are more hazardous than the product and have to be transported instead! The benefits of moving towards localized production may also have to be weighed against any possible reduction in the skill levels of local operators involved in controlling the processes.

HAZARD MANAGEMENT — AND “CAN WE DO MORE?”

The purpose of this paper is not to dampen enthusiasm, merely to focus attention on the need to avoid and control risks as part of the process development. Intensified plant can open up new, safer operating windows for many processes — but, sometimes, other issues may mean that an intensified process is not the best choice. In other cases, companies may need to take additional measures in order to ensure an appropriate level of safety. They should take the opportunity to do this at an early stage.

Industry is increasingly adopting an inherently safer approach to hazard management. One way that it can achieve this is by using procedures like the safety life-cycle model that has been developed as part of a major International standard[15]. The safety life-cycle approach sets out the procedures required for safe process design, operation and modification from conception to decommissioning.

The standard makes it clear that, from the earliest concept and definition stages, all the likely sources of hazard should be identified and recorded. An understanding of the equipment and its environment should also be developed. The extent of the risk assessments then required will depend upon the complexity of the process and the scale and nature of the risks involved. For new processes, it is recommended that the hazard and risk analysis should take place in several stages as the process design develops. This reduces the tendency to adopt, often expensive, “add on” preventive measures at an advanced stage of the process design.

It is important that all companies ensure that processes are developed with a view to avoiding and controlling safety risks. The question to be asked is ‘what more could reasonably be done to further reduce the risks?' Where process development is conducted in industrial research departments and universities, then the researchers have a key responsibility to ensure that safety is given an early and sufficient degree of consideration. This is because it is during these early development stages that most can be done to avoid risks.

In the following example, a company, in discussion with HSE, made a number of innovative changes, including intensifying the process, that both enhanced productivity and reduced the risks significantly.

Case Study 2: Six, five-tonne batch reactors, were used to produce an inorganic oxychloride by reacting the oxide with chlorine. The process was operated on a semi-batch basis. In the event of a failure, the chlorine feed would be shut off. The process had been carefully designed to prevent accumulation of unreacted materials, but there was still the hazard of cooling water leaking into the vessel and reacting violently with any unreacted contents.

The process was changed to one with a continuous loop reactor producing 500 m^3 per week of oxychloride product. The instantaneous reaction inventory was reduced by more than 2 orders of magnitude. Changing the reaction chemistry to the direct oxidation of the chloride eliminated the hazard of handling large quantities of bulk chlorine. The oxidation reaction is rapid and exothermic, but the actual temperature rise in the reactor is less than 20°C. The product acts as a diluent for the reactants in the loop.

Rather than a cooling water jacket, a tubular heat exchanger with external atmospheric pressure cooling-water sprays now cools the reaction. This has eliminated the hazard of water leaking into the reactor.

Although much can be done by inherently safer design to reduce risks, it may not be possible to eliminate all the potential hazards and maintain a viable process. Where significant residual risks remain it will be necessary to take further measures to reduce them SFAIRP or ALARP. These measures are categorized as either:

- Preventive measures, such as safety trips and alarms, designed to prevent the hazard occurring; and
- Protective measures, such as emergency relief systems, designed to mitigate the effects.

Further guidance is given in references 6 and 15.

PROCESS INTENSIFICATION NETWORK

To raise awareness of PI, including any safety considerations, the HSE, the Department of Trade and Industry and a number of industrial companies are co-sponsoring a process intensication network (PIN!), which has over 300 members. The network meets every 6 months and enables the members of the network to discuss the latest developments in PI, their benefits and potential problem areas. Further information on PIN can be found at the PIN web site at: http://www.pinetwork.org/.

CONCLUSIONS

- Companies and researchers involved in process development have duties, under both EU and UK legislation, to assess risks and, where possible, avoid them. The depth of the assessment required will depend upon the complexity of the process and the scale and nature of the risks involved.
- PI has the potential to be a major factor in the implementation of inherent safety but it needs to be considered as part of a balanced risk assessment of the plant and processes involved as, sometimes, the technology may introduce safety concerns that mean that an intensified process is not necessarily the best choice.
- Where process development is conducted in industrial research departments and universities, then the researchers have a key responsibility to ensure that safety is given an early and sufficient degree of consideration. This is because it is during these early development stages that most can be done to avoid risks.
- In order to raise awareness of PI, the HSE, in collaboration the Department of Trade and Industry, is sponsoring a network on Process Intensification. There is considerable interest in this developing field and HSE is keen to ensure that the safety implications are fully considered as part of this development.

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