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HSE CONTRACT RESEARCH REPORT No. 105/1996

PROCESS INTENSIFICATION OF BATCH, EXOTHERMIC REACTORS

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The use of Process Intensification techniques to reduce the inventory of exothermic batch reactors has been reviewed. The main techniques available are the use of compact heat exchangers, the use of intensive mixing techniques and the development of continuous processes.

Successful examples of the use of these techniques to reduce reactor inventory exist and there is potential for greater use of them. The main constraints appear to be lack of good design guides, lack of pilot scale facilities, lack of awareness and lack of allocation of process development resource to allow Process Intensification options to be explored.

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EXECUTIVE SUMMARY

The use of Process Intensification techniques to reduce the inventory of exothermic batch reactors has been reviewed.

The main techniques available are the use of compact heat exchangers, the use of intensive mixing techniques and the development of continuous processes eg. small plug-flow reactors.

Successful examples of the use of these techniques to reduce reactor inventory exist and there is potential for greater use of them.

The main constraints appear to be lack of good design guides, lack of pilot scale facilities, lack of awareness and lack of allocation of process development resource to allow Process Intensification options to be explored.

The processes that potentially could benefit most from the use of Process Intensification can be identified and visited. Therefore further information could be obtained as to the potential for and constraints to adopting Process Intensification.

1. INTRODUCTION

Exothermic chemical reactions carried out in batch reactors often represent high risk processes in the chemical industry. Process Intensification presents an opportunity to reduce the inventory of hazardous materials in a reactor and so reduce the consequence and risk of loss of containment. However, despite the potential advantages of this approach, it has not been widely adopted for batch exothermic chemical reactions.

This report has been commissioned to produce an initial review of this topic, with particular regards to enhancing the safety of chemical reactors.

2. SCOPE OF WORK

The scope of work for this report can be summarised as:

- To carry out a literature search and review of work carried out to date in the area of Process Intensification with particular emphasis on the applicability to exothermic batch reactions.
- To summarise the benefits to health & safety.
- To identify the need for further work.

3. GENERAL DEFINITION OF PROCESS INTENSIFICATION

The term 'Process Intensification' is used to describe the means by which a manufacturing process stage can be rendered more compact than the conventional standard. This implies a lower inventory and a corresponding increase in manufacturing rate for that stage compared to standard. A general review is given in Ref 1.

In the chemical industry, intensification can be applied to all stages of manufacture:

- raw materials storage
- reaction
- separation steps
- product isolation
- drying
- packaging

The 'work-up' stages following the reaction stage are usually of greater total inventory than the reaction stage itself (Ref 2 suggests that only 10% of total plant volume is in the reactor). Therefore the potential for reduction of plant size and associated costs is possibly greater than at the reaction stage. However, as the inventory of reactive and hazardous materials is higher at the reaction stage and there is also the potential for thermal runaway of the chemical reaction, then the application of Process Intensification to this stage would have the greatest improvement to health & safety.

Kletz (Refs 3,4,5,6) has discussed the concept of inherently safer plants and identified the five main approaches as:

- Intensification
- Substitution
- Attenuation
- Limitation of Effects
- Simplification/Error Tolerance

Intensification is defined as 'Using small(er) quantities of hazardous substances' which is a useful, concise definition.

Smaller quantities of hazardous substances implies smaller plant items operating at a higher production rate.

In addition the development of the use of less plant items for a given production rate could also be an example of Process Intensification if the overall inventory of hazardous substances were reduced. This is usually achieved by carrying out more than one operation in a vessel and optimisation of the vessels cycle times. Similarly, improved scheduling techniques for batch operations may reduce overall inventory but not necessarily the hazardous materials inventory.

However, neither of these latter approaches have been included within the scope of this report.

4. GENERAL OVERVIEW OF PROCESS INTENSIFICATION

To achieve Process Intensification the rate limiting step of the particular stage of a process has to be identified and then improved by increasing the achieved rate.

4.1 Improved Mixing

Mixing of components in the same phase or different phases is a mass transfer operation. The rate of mixing depends upon the fluids' physical properties and the design of the mixing equipment.

In general terms, the smaller the inventory of a plant item the faster is the mixing rate due to the reduced dimensions. In addition, the higher the intensity of the induced mixing action the higher the mass transfer rates become.

Therefore, small volume mixers designed to give high mass transfer rates offer an opportunity to reduce overall inventory where the mixing of components is the rate limiting step.

Mass transfer is often rate limiting in multi-phase systems so perhaps these offer the greatest benefits from Process Intensification.

Applications for batch reactors are discussed in Section 5.2 but other applications may be:

- Liquid/liquid mixing in a static mixer to replace a vessel for mixing.

- Gas/liquid mixing (usually absorption of gas in liquid) in a static mixer or an eductor. An example is the injection of carbon dioxide into beer in the brewing industry.

- Addition of solids to the hopper feed of a high shear mixer to incorporate the solids directly into a recirculating liquid loop.

- Injection of liquids into a pumped recirculation loop using the pump itself as a mixing device, possibly aided by the liquids flowing through an appropriate heat exchanger or intense mixing device.

- A centrifugal fan fitted with a novel flexible fibre impeller (rotating mop) has been tested for dust removal and some unreported work on scrubbing(Ref 7).

- The use of rotating beds of packing or plates (HIGEE) to aid performance (Ref 7, Ref 8 and Ref 9).

4.2 Increased Rate of Heat Transfer

If heat transfer is the rate limiting step in a process stage then an increase in heat transfer rate can reduce the inventory required for a given production rate.

There are many types of heat exchanger available and development continues to:

- increase the overall heat transfer coefficient
- improve mechanical integrity
- widen the range of materials of construction

The result of this is that there is a range of high performance and compact heat exchangers available that can be used to 'design out' any heat transfer limitations.

The design is dependent upon the fluid's properties and the thermal load but is effectively independent of the specific process chemistry.

Therefore, generic design methods have been developed and are considered reliable for a wide range of types of heat exchanger (Ref 10).

In fact the equipment supplier often carries out the sizing calculations.

Overall, the use of available high performance heat exchangers to reduce inventory offers a major opportunity.

4.3 Improved Separation Techniques

A key stage in most chemical plants is the separation stage or stages downstream of the reactor. The large volumes of these stages, perhaps as much as 90% of the total plant inventory (Ref 2), dictate that Process Intensification should be of relevance. A recent overview is given in Ref 11 which indicates that 40% of the capital cost of commodity chemicals plants is for separation.

The use of rotating equipment to generate acceleration fields to aid separation has received significant attention in the literature (Ref 7). In this reference Ramshaw describes various scrubbing, distilling, absorbing and dedusting equipment. All of these offer the potential to reduce inventory but are not commonly in use. The very recent overview (Ref 12) suggests that fouling is a major technical constraint. A study of the absorption of carbon dioxide into aqueous amines has shown the dependence of absorption efficiency on viscosity (Ref 13).

Membrane processing has potential benefits over conventional techniques when applied to dilute process streams. In such cases lower inventories are possible due to much improved separation performance and efficiencies. At present its use is mainly in product recovery and by-product recovery.

5. BATCH EXOTHERMIC REACTORS

5.1 Overview

A large number of chemical reactions are exothermic and are carried out in batch reactors fitted with some means of charging the reactants, mixing them and removing the heat generated.

The batch reactor is versatile in that it can be used for almost any type of reaction. In particular it is suitable for multiproduct operation where different products can be manufactured in the same plant in the form of campaigns.

In addition, the techniques applied to 'scale-up' from the laboratory batch flask to the full scale batch reactor are culturally well established in many companies.

One hazard of the use of batch reactors is the potential for thermal runaway resulting in loss of containment. If the heat generation rate of the reaction exceeds the reactor's cooling rate then the batch temperature will increase which increases the heat generation rate and the reaction accelerates out of control. This, of course, can only occur if sufficient quantities of reactants are present in the reactor.

The energy released from a thermal runaway is dependent upon the size of the inventory as are the subsequent effects of the release of material to the environment. Therefore the smaller the inventory the lower the risk for each particular design. One attempt to quantify this effect is recorded in Ref 1 (page 11) where the reduction of a reaction from $14m^3$ to $0.5m^3$ reduced the overpressure from vessel rupture at 15m from 0.23bar to 0.043bar.

Potentially, Process Intensification can significantly reduce the inventory of a reactor and hence reduce the consequences and risk of a thermal runaway. This concept has been reviewed many times in the literature (Ref 4, Ref 5).

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The technique that can be applied to achieve intensification depends upon the rate limiting step since in a typical reactor there are several simultaneous mechanisms operating. As a minimum there are simultaneous unsteady-state mixing, reaction and heat removal.

The literature records several successful developments where significant reductions in a reactor have been achieved, for a given production capacity. Specific examples are discussed in the relevant sections below.

The distinction between gradual development such as improved tower packings, and more rapid developments such as changes in catalyst, particle size or shape is made in Ref 14, where the rates of improvement in reactor intensification are given for:-

• mercury cells in chlorine plants	= 6.9% improvement per annum
• nickel smelting	= 60% step change
• lime kilns in soda ash plants	= 4.0% improvement per annum
• reactor - regenerator in fluid catalyst cracking	= 100% step change

5.2 Improved Mixing

Where liquid/liquid mixing is inherently poor such as with separate reactant phases and/or high intensity systems, the predispersion of one liquid reactant in the other liquid phase recirculatory around the reactor may reduce the overall volume. This would be due to more intense mixing in an external eductor or static mixer than achievable with the reactor agitation system.

Limited specific literature references were found relating to batch reactions although there are several actual examples in industry.

When one reactant is in the gas phase and requires mixing into a liquid reacting phase then mass transfer is often the limiting step. Such systems are the hydrogenation of organic compounds to chemically reduce them. Traditionally this can be achieved by sparging hydrogen into the reactor which is non-vented and kept under pressure to maximise the concentration driving force.

Reactor pressure controls the addition rate of hydrogen which is equivalent to the reaction rate in the reactor. For the highly exothermic reduction of dinitro aromatic compounds (Ref 15) external loop circulation through a gas injection system (Buss loop) and external heat removal is claimed to give the smallest reactor volume.

The efficiency of gas injection renders the rate limiting step as one of heat transfer.

Other non reported processes have been built which include gas eductors to draw the reactant gas into an intense liquid mixing zone where gas absorption rates are high and overall reaction volumes reduced from a traditional configuration.

One report using a loop eductor for chlorine addition (Ref 1 page 12) demonstrates a reduction from an $8.0m^3$ batch reactor to a $2.5m^3$ loop reactor, an increase in productivity of 43% (overall improvement 4.6 times) and better gas absorption efficiency.

5.3 Increased Heat Transfer

Intensification of Heat Transfer

A batch reactor traditionally has been fitted with a jacket or an internal coil or an external 'half-coil' (that acts in a similar manner to a jacket).

These configurations may limit the heat transfer rate and hence prolong the reactor cycle time and increase the inventory.

A jacket is inherently limiting in heat transfer area.

In addition the desired overall heat transfer coefficient to meet the minimum cycle time criterion cannot simply be designed into the system by specifying a suitable agitator since this is also limited by other design criteria.

The use of an internal coil creates a larger heat transfer area which is limited in size by the geometry of the vessel but also interacts with the mixing characteristics. In effect, a coil tends to 'fully baffle' the vessel which minimises the vertical mixing. In addition the vessel design and maintenance procedures have to allow for the installation and removal of the coil by using a flanged cover.

A batch reactor can be fitted with a pumped recycle loop through an external heat exchanger. This configuration has the effect of dissociating the agitator design from the heat transfer design and effectively eliminating any limitations on the desired heat transfer rate. Therefore, the reactor cycle time should be limited by the reaction rate.

Further advantages can be:

- external heat exchangers can be of a different material of construction from that of the reactor. For example a glass lined reactor can have a high nickel alloy plate heat exchanger. Therefore the heat transfer is not limited by the restricted materials of construction available for the reactor.

- external heat exchanges can be designed to give good performance for high viscosity fluids either by conventional or intensified designs. (Ref 10)

- the reactor materials of construction need not be relevant to heat transfer and so a wider choice is available eg. PTFE lined steel reactor.

- the possibility of in-line addition and mixing of reactants may be facilitated.

- the pump generated batch fluid pressure in the external heat exchanger can be designed such that it is greater than the service fluid so that any pin-hole leaks are one-way. This concept whilst generally correct requires a full assessment for any particular application to ensure that it is a real advantage.

- the provision of mixed services (cooling water, hot water, steam, refrigerated brine) to the external heat exchanger can be simpler to operate due to the service side volume being smaller than a jacket or coil.

The perceived disadvantages of an external heat exchanger can be:-

- additional plant items could increase the costs. However, if the reactor discharge pump is also used for recycle the difference in costs may not be relevant.

- the recycle loop flanges and the external heat exchanger are potential sources of leaks, although the increase in risk may be very small.

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- pump failure leads to total loss of heat transfer. However, this is similar to failure of the agitator in a jacketed vessel where the heat transfer could effectively fail if the agitator failed. In addition dual pumps can be installed.

5.4 Increased Reaction Rate

Where the reaction rate is limited by the chemical kinetics the rate can be increased by increasing reactant concentration, increasing temperature or using a catalyst.

In many areas of the speciality chemicals or fine chemicals industry considerable development effort is expended on process improvements. Often these continue to occur after the process for a new product has been established.

For successful products this development effort often seeks to ‘debottleneck’ the production capacity by increasing the reaction rate.

Each development is specific to the particular process and its chemistry and is outside the scope of this report, but perhaps it is at this stage of process development that Process Intensification should be addressed, as well as at the initial research stage.

It is perhaps worth noting that electrochemical processes (eg the Kolbe Reaction, where electrolysis of carboxylate ions results in the decarboxylation reaction then the resulting radicals combine to form the symmetrical dimer) can offer an alternative reactor type of possible low inventory for very specific reactions. No current work was discovered.

5.5 Continuous or Semi-Batch Operation

It is usual for an exothermic batch reaction to be carried out by initially batch charging the reactor with all the materials, except for one of the reactants. This reactant is charged at a controlled rate over a prescribed period of time so that the rate of reaction and rate of release of heat are controlled. This enables the reactant feed to be stopped and the reaction effectively stopped if any abnormality occurs in the processing of the batch.

Where this technique is not possible, often due to side reactions produced if one reactant is in gross stoichiometric excess, then both reactants can be added simultaneously. The reactor is charged with all the materials (eg solvent) except for the two reactants, although a small amount of one reactant may be batch charged to ensure that it remains in slight stoichiometric excess. Then both reactants are charged at a controlled rate over a prescribed period of time.

As well as various emergency trip devices stopping the feed(s) if there is a process abnormality (eg agitation failure or low temperature) there has been development of mathematical methods to calculate the progress of the reaction to prevent excessive accumulation of reactants (Ref 16, Ref 17, Ref 18).

These techniques are designed specifically to reduce the risk of a run-away reaction by reducing the inventory of one or more reactant in the reactor. Therefore whilst not reducing the overall reactor volume they do reduce the reactant volume and could be regarded as a subset of Process Intensification.

One long established method of reducing inventory by a significant amount is to use a continuous process. The example of Ref 19 demonstrates a size reduction from 300 litres to 25ml by developing a continuous reactor for the reaction of sulphuric acid with hydrogen peroxide to Caro's acid (H_2SO_5).

Tubular reactors (plug flow reactors) have been used extensively in the large scale petrochemicals industry and have been designed to replace batch reactors in some instances.

One example is the oxiethylation of alcohols to produce nonionic surface active agents (Ref 20). This paper concluded 'that the single-tube reactor is the most convenient apparatus providing the best heat transfer intensification. The reaction heat removal intensification can be realised due to the high tube velocity'.

In most cases, converting a batch process to continuous mode would significantly reduce the volume of the reactor. However, the successful conversion would require appropriate development resource to undertake the necessary experimentation and design, which requires allocating in good time, before any business decisions to invest in plant expansions are made.

Other examples of converting a batch reaction to continuous mode are recorded in Ref 1 and Ref 6 and are:-

- 11m^3 batch reactor volume reduced to 0.4m^3 CSTR (continuous flow stirred tank reactor)
- overall improvement by 4.6 times for a batch chlorinator to a recirculating loop/gas eductor system
- Nitroglycerine development from batch to CSTR reducing inventory by 1000 times

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6. IMPLEMENTATION OF OPPORTUNITIES

6.1 Current Work

Current work on Process Intensification is carried out either within the manufacturing companies on specific process development or at an academic institution carrying out research.

Manufacturing companies tend to carry out little research work in this area unless it is specifically targeted at a particular process. For example as a means of expanding production capacity.

Reporting of this type of work is sporadic and often hampered by commercial confidentiality. Reports can often only appear within process patents under the product name, although this is not necessarily a reliable source of determining current work.

The academic institutions, on the other hand, do publish their work and at present the current research work being carried out is at:

University of Newcastle Upon Tyne, Department of Chemical and Process Engineering

University of Bath, Department of Chemical Engineering

University of Birmingham, Department of Manufacturing and Mechanical Engineering

UMIST, Department of Chemical Engineering

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6.2 Constraints and Opportunities

6.2.1 Process Intensification of Batch Exothermic Reactors

Process Intensification potentially can be applied to all stages of a process but this report covers the reaction stage only.

The main areas of opportunity to cover the reaction are:

- *Increased Rate of Heat Transfer*

The design of compact heat exchangers (eg plate heat exchanger) is well established and reliable. When fitted to a recirculating loop on a batch reactor this approach effectively removes most heat transfer limitations on the overall reactor design.

The only potential disadvantage is that the batch is no longer 'contained' within the reactor during reaction. However, since the reactants are usually fed via pumped feedlines this risk should be acceptably small.

- *Improved Mixing*

This involves the use of an external recirculation loop to intensely mix a reactant into the recirculating batch to reduce the mixing time. The use of static mixers or eductors or equivalent are required to effect the mixing.

- *Continuous Processing*

The use of semi-batch techniques to reduce the inventory of hazardous materials in the reactor or the use of CSTR reactors or Tubular (Plug Flow) reactors to considerably reduce the reaction volume.

6.2.2 Development of New Processes

In the industries that use batch reactors the development of a new process (or improved process) takes place initially in the chemical laboratory. This is done using standard laboratory equipment as batch reactors which can be adopted to investigate most reactions efficiently.

This initial laboratory research eventually becomes the preproduction laboratory development work specifically aimed at defining the production process.

At this stage the concepts of Process Intensification could first be explored.

The production plant's engineering design is often carried out in parallel with the preproduction laboratory development in order to reduce the overall time before a new product commences production and the company earn income from its sales.

Once built and commissioned the successful process will continue to be developed in order to reduce costs, increase production capacity or improve product quality. Process Intensification could also be explored at this stage and incorporated, for example, as part of a debottlenecking exercise. However, the Process Intensification development work has to start sufficiently early to allow for the longer development time compared to a conventional approach.

6.2.3 Constraints

The adoption of Process Intensification for batch reactors is underexplored and little successful development is reported. However, when a successful development is reported (Ref 19) the results can be very impressive (reduction of reactor volume from 300 litres to 25ml).

The technical, resource and cultural constraints that have to be overcome to successfully develop an intensified process are not usually reported. The technical description of success tends only to describe the work in a logical, scientific way that may even appear to be self-evident and leave the reader wondering why more intensified processes are not developed.

Clearly the successful results of Process Intensification are worthwhile yet clearly Process Intensification has not 'taken off' as a major means of process improvement.

The major constraints may be:

- failure to allocate resources and development effort to explore opportunities
- failure to allocate resources soon enough
- the perceived technical risks
- the cultural attitude and systems

Table 1 below suggests a subjective ranking of each Process Intensification technique versus each constraint.

TABLE 1: CONSTRAINTS ON PROCESS INTENSIFICATION

Process Intensification Technique	Constraint		
	Cultural Resistance	Technical Risk	Resource and Time Required
Compact Heat Exchangers	Moderate	Low	Low
Loop Induction of Reaction Fluid	High	Moderate	Moderate
Continuous Processing	High	High	High

Compact heat exchangers operating in a recirculating loop around the batch reactor are straightforward to design and specify. The only area of technical risk is usually concerned with the specification of an adequate material of construction.

Some parts of industry may be resistant to their use due to lack of familiarity or concerns over potential leakage of the conventional plate heat exchangers. Sufficient operating experience now exists for any cultural resistance to be successfully overcome.

Loop induction of reactant fluids would require a theoretical design based upon a knowledge of the design of eductors and turbulent fluid mixing in the pipe downstream of the mixing device. This is available but is not necessarily convenient to find or use.

In addition, most companies would want confirmation that the process chemistry would proceed satisfactorily in this new configuration so a pilot scale reaction would tend to be required. Such an approach requires the availability of an appropriate rig, the time to design the connections to the appropriate reactant streams and the development time to successfully demonstrate the technique.

The technical risks would tend to be associated with the detailed design of the mixing device to achieve the desired effect effectively.

Changing to continuous processing is a major change that tends to affect not only the reaction stage under consideration but the rest of the process as well since a continuous reactor and batch isolation/work up stages are usually cumbersome to operate.

The overall advantages/disadvantages of batch versus continuous are many but the major points can be summarised as in Table 2.

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TABLE 2: BATCH V CONTINUOUS PROCESSING

Batch Processing		Continuous Processing	
Advantages	Disadvantages	Advantages	Disadvantages
Similar to laboratory developed 'recipe' Scale-up rules accepted and straightforward Culturally accepted Robust processing not requiring precise flow control Inferior Quality Product can be reworked easily Small quantities of reactants easily charged Handles multiple feeds easily Charging of solids or difficult fluids straightforward Plant is flexible and can be modified for other processes Several stages can be carried out in same vessel	Expensive for large tonnages Large reactor (and other vessels) volumes Tends to be labour intensive	Less expensive for large tonnages Low inventory Low labour costs Automatic process control straightforward	Requires significant development time and cost Design and scale-up tend to be 'bespoke' for each process Culturally difficult to accept for batch orientated industries Processes that are not tolerant of minor upsets can give product quality problems (less robust) Small quantities difficult to handle, as are difficult fluids or solids Plant not flexible Each process stage needs separate plant items

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To change a batch reaction to a continuous process would require considerable effort and resource probably most easily accomplished as part of a production capacity expansion. If this initiation of action is left too long then there is not sufficient time to develop a Process Intensification option.

In addition the laboratory scale apparatus required to develop a continuous process can be time-consuming to acquire. For example, measuring and controlling small flowrates of reactants is difficult to do accurately without specialised equipment. In addition the laboratory continuous reactor may need to be quite small because they are so productive; otherwise large quantities of reactants would be needed.

One advantage when designing a continuous process for the 'batch processing' industries is that scale-up from laboratory pilot to full scale is relatively simple. In fact the problem is to scale down to the laboratory.

Finally the design and scale-up often needs some understanding of the reaction kinetics in order to design and scale-up the equipment, which can be difficult and time consuming to obtain.

6.3 Way Forward

The way forward to both encourage industry to explore Process Intensification techniques and to encourage research establishments to provide the fresh ideas and techniques is complicated but can be broken down into its component parts.

6.3.1 Industry Attitudes

Based on this initial review, industrial development departments could be targeted with a structured questionnaire to test the opportunities for Process Intensification and the constraints in progressing the subject.

In addition, selected site visits could be undertaken to supplement the data and test results.

The questionnaire should cover awareness of the techniques, the perceived advantages and constraints and the likelihood of opportunities within that company. The potential barrier to development of Process Intensification for pharmaceutical processes and their licensing procedures could also be investigated.

6.3.2 Design Techniques

The design techniques for Process Intensification may not be collated conveniently, for example, the design of an intensive mixer for a recirculation loop.

The current sources of design techniques should be reviewed, assessed and any gaps highlighted. The need for design guide(s) should also be assessed and tested with industrialists.

6.3.3 Pilot Scale Facilities

To achieve successfully a significant reduction in inventory by using Process Intensification would almost certainly require a pilot scale trial.

The provision of pilot facilities should be assessed with a view to determining what devices need to be available, if they are available, where they should be located and how they could be used with actual industrial processes. It may need an 'off the shelf' availability of equipment to encourage appropriate development.

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6.3.4 Target Processes

This report is targeted at the Process Intensification of exothermic reactions carried out in batch reactors so that inventory of hazardous materials can be reduced.

It is possible to target most of the reactions with the highest heats of reactions, those that have a history of incidents and the companies and location sites of their manufacture. Therefore, a proactive approach could be taken to specifically examine the possibilities for Process Intensification for a specific process or processes. Examples could be polymerisations, sulphonations, nitrations, halogenations, Grignard reagents, phosgenations etc.

6.3.5 Other Processes

The concept of Process Intensification could apply also to certain existing continuous processes where reactor inventory is considered large and hazardous.

6.3.6 Process Intensification Progress

Previous well researched areas of Process Intensification could be investigated to explore the reasons why they did not become more accepted (eg HIGEE distillation). This may provide insight into the most likely successful approach to be taken in the future with other similar concepts.

6.3.7 Process Intensification for Separation Processes

This report concentrates on reactors but there are opportunities for inventory reduction outside the reactor system which can be more straightforward to develop.

Consideration could also be given to these areas to reduce overall plant inventory.

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7. CONCLUSIONS

- Process Intensification has been used to reduce batch reactor inventory by significant amounts.
- Significant reduction of reactor inventory should significantly reduce the consequences of loss of containment.
- Some development work on Process Intensification is being carried out by Universities and Industry.
- There are constraints to applying Process Intensification to an industrial process that restrict its use.
- The main constraints are lack of good design guides; lack of facilities to pilot industrial processes; the possible failure to allocate development resource early enough in a project to allow a Process Intensification option to be developed and possibly lack of awareness.
- Further information from industry could be obtained by use of a structured questionnaire.
- Selected visits to the identified industrial contacts would provide more detailed information.
- The most hazardous batch exothermic reactions can be identified and the manufacturing sites visited to obtain more information.
- Certain large inventory continuous processes reactors could benefit from Process Intensification.
- Eventually a high profile seminar could be arranged to present the findings from the above; present industrial successes; discuss the constraints and present the current work being carried out within the Universities.

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