The obtrusive towers of today's chemical complexes should be replaced with more compact and inconspicuous equipment

Process Intensification and Green Chemistry

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When the concept of process intensification was developed within ICI in the late 1970s, the main intention was to make big reductions in the cost of processing systems, without impairing their production rate. The term 'Process Intensification' describes the strategy of making dramatic (100-1000 fold) reductions in plant volume in order to meet a given production objective. It is well known that the cost of the main plant items (*e.g.* reactor, separators *etc.*) only represents around 20% of the cost of a production system, with the remainder being incurred by pipework, structural support, installation and so on. A major reduction in equipment size, with hopefully a high degree of telescoping of plant function, could lead to large cost savings by eliminating support structure, column foundations and long pipe runs.

Advantages

The degree of miniaturisation involved is that needed to generate the cash savings required. Thus volume reductions of the order of 100 times must be our target in order to secure the desired impact on costs. While an individual intensified unit may cost a little more than the conventional equivalent, (although hopefully it will not) it must generate substantial overall savings in the cost of the process system. In addition, the process intensification philosophy should be applied across the whole spectrum of unit operations used in the plant. Bearing in mind the dramatic size reduction which is sought, process intensification will probably involve novel and unusual approaches to equipment design. It is not a strategy for the faint-hearted. Herein lies one of its main disadvantages, namely the lack of new design codes to engender confidence in those who specify new equipment. Radical and unconventional approaches will be the order of the day. Many searching questions will be posed, such as the need for turbulent flow in pipes, the use of batch rather than continuous operation and the application of merely terrestrial acceleration to multi-phase systems, to name but a few. It is a sobering thought that if chemical engineers were given a free hand to

'major reductions in equipment size could lead to large cost savings' design the human digestive and metabolic system, our bodies would be much larger and require many kilowatts to operate them. On the other hand, nature operates unobtrusively with laminar flow in high density matrices (kidneys and lungs) on a semi-continuous basis, and copes with fouling problems by coughing. As scientists and engineers we should not be too arrogant to learn a few lessons from the natural world.

While cost reduction was the original target for process intensification, it quickly became apparent that there were other important benefits, particularly in respect of improved intrinsic safety, reduced environmental impact and energy consumption. Given the anticipated plant volume reductions, the toxic and flammable inventories of intensified plant are correspondingly reduced, thereby making a major contribution to intrinsic safety. This point has been well made by Trevor Kletz, who has commented that 'what you don't have cannot leak'.[1]

With regard to the environment, the intensified plant of the future will be much less obtrusive, with the distillation and absorption towers of our present chemical complexes being replaced by more compact and inconspicuous equipment, which may be hidden by the boundary tree line. In addition, the cost of effluent treatment systems will be less, allowing tighter emission standards to be reached economically. However, the most telling environmental influence of process intensification could well be in the development of new reactor design for truly clean technology. Rather than accept mere 'end of pipe' solution, we must create fluid dynamic environments which allow the intrinsic chemical kinetics free rein. We then have a far better prospect of designing reactors which operate intensively and which give high selectivity. This would facilitate the delivery of a high quality product without an expensive downstream purification sequence.

The high heat and mass transfer coefficients which can be generated in intensified equipment can be exploited to reduce the concentration/temperature driving forces needed to operate energy transformers such as heat pumps, furnaces, electrochemical cells *etc*. This enhances the equipment's thermodynamic reversibility and hence its energy efficiency. For example we have shown at Newcastle that the application of elevated acceleration fields to a simple chlorine cell can reduce its voltage by over 0.4 V.[2] Similarly the Rotex absorption air conditioner[3] which will soon be entering

Spinning disc reactor technology

field trials, demonstrates a very high performance while avoiding the arcton/chlorofluorocarbon working fluids used in vapour compression air conditioners. Instead a water solution of mixed alkali metal hydroxides is employed. Therefore innovative applications of process intensification thinking can improve our capacity to meet the energy and global warming targets which were recently agreed at Kyoto.

The nuclear reprocessing industry is likely to be a major beneficiary of process intensification on several counts. Much of the life cycle cost associated with any nuclear operation is involved in the final decommissioning of the equipment. Intensified plant, with its dramatically reduced size and shielding requirement, allows the overall life costs to be significantly reduced. In addition, reprocessing operations must take into account the permitted inventories in each of the process units, in view of criticality considerations. This can result in operation at lower concentrations than those preferred from an economic point of view. Intensified reprocessing avoids this limitation and facilitates the use of higher, more economic concentrations.

The envisaged size reductions inevitably mean that process residence times will be much less than those we are currently used to and our control philosophy must be amended accordingly. Indeed we must ask whether we need control at all in the conventional sense of requiring ultra-rapid feedback from novel fast-response process sensors. The parallel between the slow-response Aga cooker and a fast-response gas flame is relevant here and it is common knowledge that food can be effectively prepared using either! Fast-response reactors open up the possibility of switching to more severe process conditions that would be prohibited in conventional units in view of the tendency to degrade the product. It may be possible to exploit a virtuous circle:- short residence time – higher temperature – faster kinetics – smaller reactor – shorter residence time. In a more general business sense there will be an improved ability to change the process output in response to market demand. Therefore, rather than transport hazardous chemicals on the railways and public highways, it may be feasible to operate a distributed production strategy, with economic manufacture on a customer's site as is currently done for oxygen and nitrogen. This has obvious environmental and safety advantages. However the R & D community must generate appropriate cost-effective process engineering equipment and most importantly, this must be marketed effectively so that it is widely used.

Example

The manufacture of fine chemicals is conventionally performed in stirred vessels operated batchwise to produce typically 50-5000 tonnes per annum. The drug industry operates on a similar basis but with a lower output (5-100 tonnes per annum) having a very high value. In both cases there is a very strong incentive to improve intrinsic safety by minimising process inventories and avoid reaction 'run-away'. As far as the drug industry is concerned there is also strong pressure to reduce the time needed to bring new molecules to market in order to maximise the profitable manufacturing period available within the 20-year life of the patent. Therefore regulatory authority approval for a new process will be achieved much more quickly when continuous production at the laboratory scale can be achieved for the desired rates, using proven equipment, because the need for approval at larger scale has been eliminated, *i.e.* the laboratory scale is the full scale.

Finally, in the context of reducing process labour costs, there is a strong business interest in eliminating inter-batch cleaning by operating the process continuously (on a 'desktop') while being controlled by its dedicated computer. Recent research at Newcastle University[4] has shown that spinning disc reactors (SDRs) are eminently suitable for helping to meet these business objectives for several important processes. Their key characteristic is an ability to stimulate intense heat/mass transfer between a highly sheared liquid film and the rotating disc over which it moves, or the adjacent gas phase. This allows rapid reactions which involve viscous liquids or large exotherms to be precisely controlled.

Following extensive discussions with potential industrial partners in the pharmaceuticals/fine chemicals area, it has become evident that there is considerable interest in the opportunities presented by spinning disc reactor technology. The target reactions are those which are intrinsically fast and exothermic, but which are currently limited by poor heat and mass transfer when performed in conventional stirred vessels. This can result in large inventories of hazardous material, possible reactor run-away and poor quality product. A reactor design based on spinning discs provides an excellent heat and mass transfer environment for the reacting liquid and promises to overcome these disadvantages.

SDR technology offers the possibility of a step change in manufacturing operations, particularly with respect to the following attributes:

- Ability to cope with very fast exothermic reactions (corresponding to heat fluxes of up to 100 kW/m^2 .
- Low inventory/intrinsic safety (liquid film thickness are 50-200 (μm).
- Rapid response (liquid residence times are 1 – 5 seconds).
- Easy cleaning.
- Close control (due to short residence times).

However in general it is perceived that the biggest obstacle to the adoption of SDR technology will be business process issues rather than technology. In particular, chemists involved in process development have both a lack of awareness of SDRs and a fear of 'mechanical' innovations.

At Newcastle we are tackling this problem by manufacturing prototype SDRs in our workshops and then arranging to have them operated in the laboratories of our industrial collaborators. Initial results are very promising and it is anticipated that several joint projects will emerge in order to perfect the technology for each client's application. Ultimately it is the intention to have simple proven versions of SDRs available when the process route is being developed by the chemist. Hopefully this will encourage the adoption of a continuous processing strategy from the outset, because once beakers or flasks are used in the initial process development it is very difficult thereafter to gain support for a continuous option.

It is recognised that a typical fine chemical/drug process involves many operations in addition to the reaction stage. These may be extraction, precipitation, solids removal, drying, distillation etc. In order to bring the desk top plant to reality, intensified versions of the relevant conventional equipment must be made readily available to the process research chemist, otherwise we will end up with the same old pots and pans as before. Although this is a challenging target, the business benefits justify its enthusiastic acceptance.

Conclusions

- A strategy of process intensification requires a step change in the philosophy of plant and process design.
- If effectively implemented, it will lead to major improvements in environmental acceptability, energy efficiency, intrinsic safety and capital cost.
- A major cultural change is required on behalf of chemists, engineers and managers and it is this, rather than technical difficulty, which represents the main obstacle to progress.

References

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