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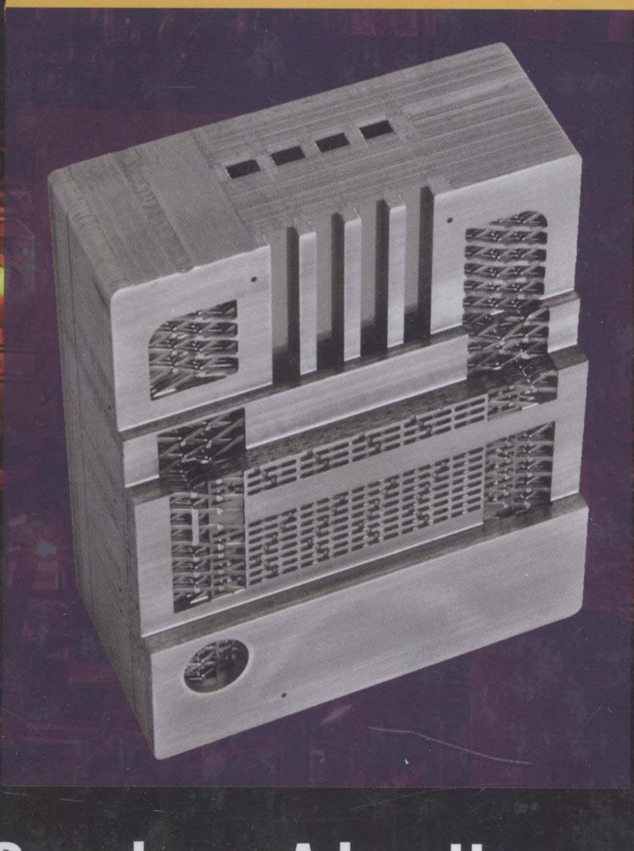
PROCESS INTENSIFICATION

ENGINEERING FOR EFFICIENCY, SUSTAINABILITY AND FLEXIBILITY



David Reay • Colin Ramshaw • Adam Harvey

Process Intensification

Engineering for Efficiency, Sustainability and Flexibility

David Reay
Colin Ramshaw
and
Adam Harvey

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FOREWORD

In the early 1990s my research team at Dow Chemical was challenged to overcome the technical barriers to create an economically viable process for making hypochlorous acid (HOCl). A number of chemical routes were documented in the literature, but no one had successfully commercialized any of the proposed routes. We selected a reactive distillation approach as the most promising. However, the conventional equipment and process technology did not meet the project objectives. We had not heard of 'process intensification' at the time, but the work of Colin Ramshaw on the rotating packed bed (Higee or RPB) was known. Believing that the Higee could solve the technical issues, we undertook its application. In fact, the RPB exceeded expectations, becoming the enabler to bring the HOCl process to full commercial status in 1999. Solving the technical challenges of the process development was only half the problem; the other half was convincing business managers, project managers, and plant personnel to take the risk to implement new technology. Not only did we have a new chemical process which no one else had been able to commercialize, but the new process was based on new equipment technology which had never been scaled up beyond the pilot scale. Though eventually successful, what we lacked in the 1990s was a broad-based understanding of process intensification principles and successful commercial examples to facilitate the discussion on risk management.

What was lacking a decade ago in terms of process principles and examples has now been supplied by David Reay, Colin Ramshaw, and Adam Harvey in this book on *Process Intensification* (PI). The authors chronicle the history of PI with emphasis on heat and mass transfer. For the business manager and project manager the PI Overview presents the value proposition for PI including capital reduction (smaller, cheaper), safety (reduced volume), environmental impact, and energy reduction. In addition, PI offers the promise of improved raw material yields. The authors deal with the obstacles to implementing PI, chief of which is risk management.

For the researcher and technology manager the authors provide an analysis of the mechanisms involved in PI. Active methods (energy added) to enhance heat and mass transfer are emphasized. A thorough look at intensified unit operations of heat transfer, reaction, separation, and mixing allows the reader to assess the application of PI to existing or new process technologies. The examples of commercial practice in the chemical industry, oil and gas (offshore), nuclear, food, aerospace, biotechnology, and consumer products show the depth and breadth of opportunities for the innovative application of PI to advance technology and to create wealth.

The final chapter provides a methodology to assess whether PI provides opportunities to improve existing or new processes. The step-by-step approach reviews both business and technical drivers and tests, including detailed questions to answer, to determine the potential value of applying PI. Not to be overlooked in this assessment process are the helpful tables in Chapters 2, 5, and 11. Table 2.5 lists the equipment types involved in PI and the sections of the book where additional information is located. Table 5.5 provides a list of the types of reactors employed in PI. Table 11.2 reviews the applications of PI.

This book on process intensification would have helped my research team to accelerate its study of the RPB (Higee) for production of HOCl, but would have also exposed us to much broader application of PI principles to other opportunities. The content would have been useful in the process of convincing the business and project managers to undertake the risk of implementing the new process and equipment. The book comes on the scene at an opportune time to influence and impact the chemical and petroleum industries as they face increasing global competition, government oversight, and social accountability. Business as usual will not meet these demands on the industry; the discipline of process intensification provides a valuable set of tools to aid the industry as we advance into the twenty-first century.

David Trent
Retired Scientist of Dow Chemical

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PREFACE

While process intensification (PI) has been with us since well before the middle of the last century in several guises, it was the work of Colin Ramshaw at ICI in the UK in the 1970s and 1980s that so dramatically illustrated what the concept could mean to chemical process plant design. Colin used several methods to allow massive size reductions in plant to be made, for a given duty, the most physically startling being the use of HiGee – high gravity fields – brought about by rotation.

Since the work at ICI, reported extensively in the press and in scientific papers, process intensification has led to substantial improvements in unit operations such as heat exchangers, reactors and separators, and has extended outside the chemical industry to impinge on other process sectors, electronics thermal management and domestic air conditioning. The number of methods for intensifying heat and/or mass transfer has increased substantially, as evidenced, for example, by the increased use of electric fields. Intensification is also an area where technology transfer has been particularly important in allowing developments to cross sectoral barriers – the compact and micro-heat exchangers used in areas from off-shore gas processing to laptop computers are an example.

This book is timely for several reasons. Process intensification can significantly enhance the energy efficiency of unit operations and improve process selectivity. It is therefore a powerful weapon in combating global warming, which is now one of the most critical issues facing mankind. In addition, intensified plant is capable of faster response to market fluctuations and new product developments. This flexibility should allow companies to compete more effectively in rapidly changing markets.

The book is intended to provide the background required by those wishing to research, design or make and use PI equipment. The data given will be of value to students, researchers and those in industry. With chapters ranging from the history of PI to its implementation in the field, via extensive technical descriptions of equipment and their application, the book should be of value to anyone interested in learning about this subject.

Extensive appendices will point readers to those able to assist in more detail by supplying PI plant, developing new systems, or providing in-depth reviews of specific areas of the technology.

D.A. Reay
C. Ramshaw
A.P. Harvey

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INTRODUCTION

Process intensification (PI) may be defined in a number of ways. The chemist or chemical engineer will appreciate the two-part definition used by one of the major manufacturers of PI equipment:

- PI significantly enhances transport rates
- It gives every molecule the same processing experience.

This definition can be usefully interpreted as being a process development involving dramatically smaller equipment which leads to:

1. Improved control of reactor kinetics giving higher selectivity/reduced waste products.
2. Higher energy efficiency.
3. Reduced capital costs.
4. Reduced inventory/improved intrinsic safety/fast response times.

The heat transfer engineer will note that 'intensification' is analogous to 'enhancement', and intensification is based to a substantial degree on active and, to a lesser extent, passive enhancement methods that are used widely in heat and mass transfer, as will be illustrated regularly throughout the book.

Readers will be well placed to appreciate and implement the PI strategy once they are aware of the many technologies which can be used to intensify unit operations and also of some successful applications.

Perhaps the most commonly recognisable feature of an intensified process is that it is smaller – perhaps by orders of magnitude – than that it supersedes. The phraseology unique to intensified processes – the 'pocket-sized nitric acid plant' being an example – manages to bring out in a most dramatic way the reduction in scale possible, using what we might describe as 'extreme' heat and mass transfer enhancement (although one is unlikely to put a nitric acid plant in one's pocket!). Cleanliness and energy-efficiency tend to result from this compactness of plant, particularly in chemical processes and unit operations, but increasingly in other application areas, as will be seen in the 'applications' chapters of this book. To this may be added safety, brought about by the implicit smaller inventories of what may be hazardous chemicals that are passing through the intensified unit operations. So it is perhaps entirely appropriate to regard PI as a 'green' technology – making minimum demand on our resources – compatible with the well-known statement from the UN Bruntland Commission for '......*a form of sustainable development which meets the needs of the present without compromising the ability of future generations to meet their own needs*'.

In the UK the Institution of Chemical Engineers (IChemE), in its recently-published *Roadmap for the Twentyfirst Century*, coincident with it celebrating 50 years since it was awarded its Royal Charter, sets the scene for Process Intensification in the context of sustainable technology, (Anon, 2007):

> *'As chemical engineers we have readily accepted the principle of the economy of scale, and as a result have designed and built ever larger production units, increasing plant efficiency and reducing per unit costs of production. The downsides of this policy include increased safety and environmental risks arising from higher inventories of hazardous material, the economic risk of overcapacity from simultaneous multiple world-scale plant expansions, and the legacy effects of written down plant impeding the introduction of new products and technology.*
>
> *New concepts such as process intensification, flexible, miniaturised plants, localised production and industrial ecology must become mainstream and we must continually reassess our approach to plant design and the acceptance of innovative concepts to render the chemical industry sustainable.*
>
> *IChemE believes that the necessary change in business strategy to speed the introduction of innovative and sustainable technologies should be led from the boardroom, facilitated and encouraged by chemical engineers at all levels in industry, commerce and academia'.*

The compact heat exchanger, one of the first technologies addressed in this book (in Chapter 4), is a good example of an *evolutionary* process technology which now forms the basis of very small chemical reactors (and possibly new generations of nuclear reactors), as well as being routinely used for its primary purpose, heat transfer, in many demanding applications. The rotating distillation unit, known as 'HiGee', invented over 25 years ago by co-author Professor Colin Ramshaw when at ICI, represented a *revolutionary* change (in more ways than one) in process plant size reduction – in the words of Bart Drinkenberg of the major chemical company, DSM, able to reduce distillation columns '*...the size of Big Ben, to a few metres in height*'.

As well as building awareness of what remains, to many, an obscure technology a further aim of the book is to show that process intensification, whether its technology has evolved over the years or involves a step change in thinking, is not limited to chemical processes. The electronics industry, first with the transistor and then with the chip, has achieved amazing performance enhancements in modern microelectronic systems – and these enhancements have necessitated parallel increases in heat removal rates, typified by intensified heat exchangers and even micro-refrigerators. Note that 'intensification' has a slightly different connotation here – the micro-refrigerator used to cool the electronics chip does not have the cooling capacity of its large counterparts, whereas the HiGee separator or the plate reactor, as will be demonstrated later, do retain the capability of their ubiquitous, but now obsolescent, large predecessors.

It is highly relevant to note that some of the most compact intensified process plants are fabricated using methodologies developed within the electronics sector – micro-technology and MEMS, (micro-electro-mechanical systems) are synonymous with modern manufacturing technology and also with intensification. The Printed Circuit Heat Exchanger (Chapter 4), as its name implies, bears not a small relationship to electronics.

Biological and biochemical systems can also be intensified – food production and effluent treatment are examples. In its Roadmap the IChemE extends its comments to the food industry, again citing PI as an important contributor:

> *'Innovation within the food industry bridges a spectrum from far market and blue sky, usually supported by the larger organisations, to incremental development, often the preserve of small companies. Chemical engineering has an essential role in areas such as the scale-up of emerging technologies, e.g. ultra high pressure, electrical technologies, pulsed light; the control of processes both in terms of QA (Quality Assurance) approaches (e.g. HACCP/HAZOP/HAZAN) and process engineering control approaches; the validation and verification of the effectiveness of processing systems; the optimisation of manufacturing operations; increasing flexibility in plant and* process intensification*; and the application of nanotechnology concepts to food ingredients and products. Commercial viability of innovative technologies is key, as is the consumer perception of the risks and benefits of new technologies. Education is vital in informing such perceptions. The environmental impact of the new approach will be one of the key factors.*
>
> *Considering the range of these topics, it is clear that some are far from application in the manufacturing sector of today and require fundamental research to develop the knowledge of the science that underpins the area, together with the engineering approaches necessary to implement the new technology in the manufacturing arena. This is clearly a role for strategic research funding within the academic community. It is important to encourage the blue sky development of science on a broad front compatible with the key challenges for the industry. Sustainability is vital and must be an active consideration for all involved in the food sector'.*

While those processes involving enzymes tend to progress at rather leisurely paces, some fermentation processes may be limited by oxygen availability and therefore susceptible to mass transfer intensification. The ability to intensify such reactions remains attractive in food production, some pharmaceutics production and waste disposal – in fact reactors such as those based upon oscillatory baffle movement are becoming increasingly a commercial reality – typified by the work of co-author Dr Adam Harvey at Newcastle University on his 'portable' bioethanol plant. (As an aside, a literature search of process intensification inevitably encompasses intensive agriculture – PI on a grander scale!)

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