

INDUSTRIAL MICROCHANNEL DEVICES – WHERE ARE WE TODAY?

Lee M. Pua¹ and S.O. Rumbold²

Heatric division of Meggitt (UK) Ltd
46 Holton Road, Holton Heath, Poole, Dorset, BH16 6LT, United Kingdom

¹ Email: lee.pua@heatric.com

² Email: svend.rumbold@heatric.com

ABSTRACT

Heatric has been involved in the commercial design and manufacturing of “micro/milli” scale heat exchanger core matrices called Printed Circuit Heat Exchangers (PCHEs) since 1985. These core matrices are formed by diffusion bonding together plates into which fluid flow microchannels have (usually) been formed by photo-chemical machining. Complex fluid circuitry is readily implemented with this technique. Diffusion bonding is a ‘solid-state joining’ process creating a bond of parent metal strength and ductility. The complete microchannel heat exchangers are highly compact, typically comprising about one-fifth the size and weight of conventional heat exchangers for the same thermal duty and pressure drops. PCHEs can be constructed out of a range of materials, including austenitic stainless steels suitable for design temperatures up to 800°C, and nickel alloys such as Incoloy 800HT suitable for design temperatures more than 900°C. Single units ranging from a few grams up to 100 tonnes have been manufactured.

Currently there are thousands of tons of such microchannel matrix in hundreds of services – many of them arduous duties on offshore oil and gas platforms where the size and weight advantages of microchannel heat exchangers are of obvious benefit. Whilst these matrices are predominantly involved in thermally simple two-fluid heat exchange, albeit at pressures up to 500 bar, PCHEs have also been used for many multi-stream counter-flow heat exchangers. However the field of applications is very varied, including specialised chemicals processing, and PCHEs are even to be found orbiting the Earth in the International Space Station!

Due to the inherent flexibility of the etching process, the basic construction may readily be applied to both a wider range, and more complex integration of process unit operations. Chemical reaction, rectification, stripping, mixing, and absorption, as well as boiling and condensation, can be incorporated into compact integrated process modules. Crucially, the resulting degree of compactness has led printed circuit technology to be the enabling technology in certain duties. Techniques for chemical coating onto the surfaces of channels continue to evolve, with applicability both to protective coatings and catalytically active coatings. We will describe a selection of innovative printed circuit technology examples.

Alongside the more esoteric, Heatric is actively extending printed circuit technology to adapt to new market opportunities such as nuclear power generation plant and fuel cell systems. These applications perhaps represent two extremes of the both size and process integration, and thus aptly serve to demonstrate the range of industrial use of microchannel devices.

INTRODUCTION

Our intention in this paper is to provide an overview of Heatric’s experience with industrial microchannel devices, their applications to date (both conventional and novel) and future opportunities.

The Printed Circuit Heat Exchanger (PCHE) is an established micro- and minichannel heat exchanger technology, originally invented as a result of research performed at the University of Sydney in the early 1980’s.

Heatric was formed in 1985 in Australia to commercialise the concept. The passage dimensions in the PCHEs span the range of ‘microchannels’ (under 200 micrometers) to ‘minichannels’ (up to 3 mm). The typical hydraulic diameter in a PCHE passage is in between 700 µm and 1.5 mm. This translates into significant space and weight savings due to enhancement in heat transfer coefficients and surface density. [Note: except in specific instances where the distinction is relevant, we have generally used the term “microchannel” to embrace both micro and minichannels.]

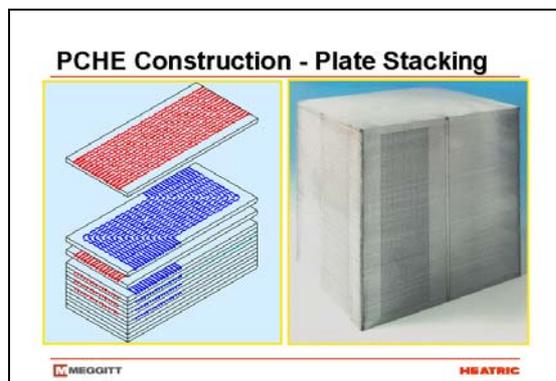


Following Heatric’s move to the UK in 1989, PCHEs rapidly gained acceptance in the offshore industry. Many thousands of tonnes of microchannel PCHE core have since been manufactured and delivered into a wide range of arduous duties. Other applications include LNG, ethylene oxide, sulphuric acid, naphtha reforming, fuel cell systems and caustic soda plants.

More recently, Heatric has developed the Printed Circuit Reactor (PCR) concept to extend the application of microchannel devices into chemical processing, chemical reaction and fuel processing. Several PCR modules have been manufactured for demonstration purposes.

PRINTED CIRCUIT TECHNOLOGY

The compact core of a PCHE is constructed by chemically milling microchannels into flat metal plates, and then stacking and diffusion bonding the plates together into a single block. The chemical milling technique is analogous to that used for the manufacture of electronic printed circuit boards, giving rise to the “Printed Circuit” exchanger name.



Diffusion bonding is a high temperature solid state joining process that promotes grain growth across the metal boundaries, resulting in a join exhibiting parent metal strength and ductility.

Multiple diffusion-bonded blocks may be welded together to form larger units, before headers, nozzles and flanges are welded on to complete the exchanger. However, smaller exchangers may be installed directly within ducting, and compression fittings may be used on smaller nozzle sizes. Other configurations are possible, depending on service requirements.

Microchannel matrices can be manufactured in a range of high performance materials, including austenitic stainless steels, 22Cr duplex, copper, titanium, Incoloy 800HT and others, permitting use in wide range of application, from cryogenic temperatures to over 900°C.



MICROCHANNEL HEAT EXCHANGERS

Offshore Hydrocarbon Processing

Completed microchannel PCHEs are highly compact, typically about one-fifth the size and weight of conventional heat exchangers, for the same thermal duty and pressure drops. The biggest market for the PCHEs has been in offshore gas processing. To date, more than 500 PCHEs have been supplied to over 120 projects, spanning geographical locations from the North Sea to Indonesia.



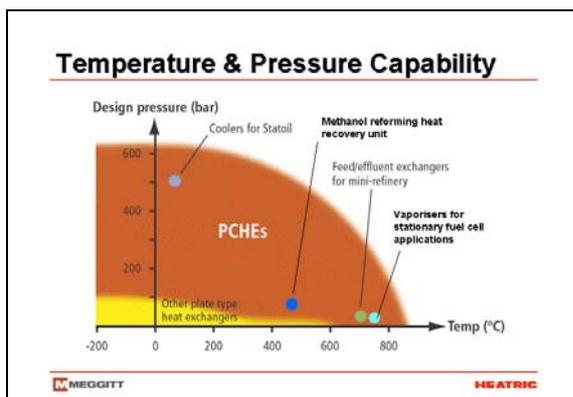
The unit shown below is perhaps the biggest industrial microchannel device in the world. It is a PCHE weighing over 100 tonnes, with millions of minichannels, currently in

service on an offshore platform. Since the size and weight of this compact PCHE are only 20% of the conventional shell-and-tube exchanger, it enabled significant savings in deck space, and thereby substantially reduced the overall project cost.



High Pressure Applications

Unlike other plate type exchangers, microchannel PCHEs are high integrity heat exchangers, and several PCHEs are in service operating at up to 500 bar, whilst design pressures of over 600 bar are possible.



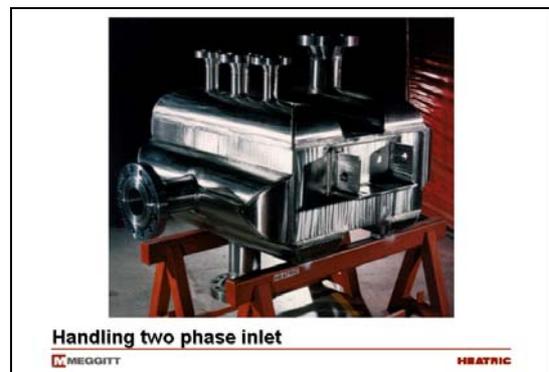
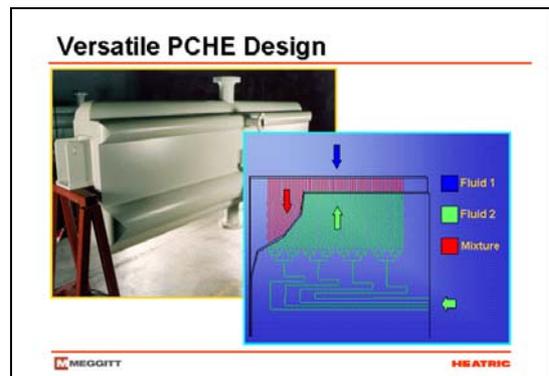
Mechanical design of PCHEs is normally to ASME Section VIII Division 1. However, PCHEs can be designed to other international pressure vessel codes, and they have been supplied either with the ASME “U Stamp” or “CE marked”.



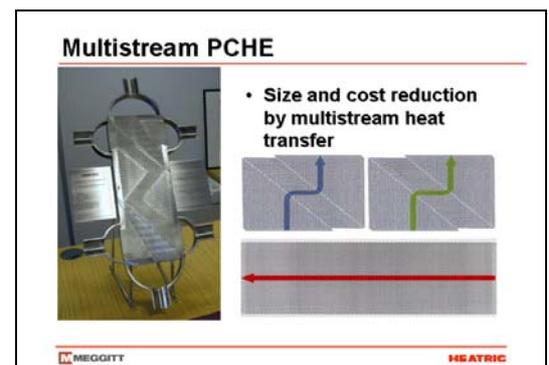
Versatile Design

In addition to the inherent design and manufacturing flexibility provided by photo-chemical machining the flow patterns, these microchannel devices may conveniently be configured to reduce the number of components in a process flowscheme.

Heat Exchange with Two-Phase Streams. By using separate vapour and liquid feeds, with channels on adjacent plates, PCHEs can be designed to uniformly distribute a two-phase stream at the inlet on a passage-by-passage basis. By assuring uniform distribution of both phases we can be confident of achieving design thermal performance, even for very high thermal effectiveness units.



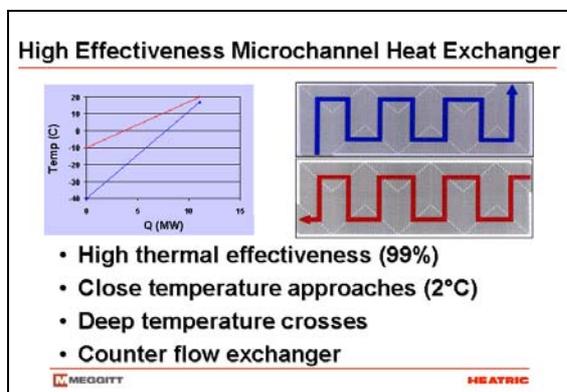
Multi-stream Heat Exchangers. Multiple streams are readily incorporated in a PCHE. Streams can be arranged in parallel, or in series, or a combination of both, to suit the process requirement. Employing multi-stream heat exchange can reduce the overall size, piping complexity and cost of a project.



High Effectiveness

The close temperature approaches, which can be achieved with PCHEs, can offer considerable cost savings. In gas cooling duties, for example, PCHEs can utilise much higher coolant exit temperatures than conventional equipment, enabling coolant flow reductions of up to 30%, with negligible impact on exchanger size and price.

By arranging microchannels in true counter-current pattern, high thermal effectiveness (99%) is possible with PCHEs. This is an attractive feature in many applications, including the next generation of Brayton cycle nuclear power plant currently being developed, where recuperation with a very close temperature approach is necessary to achieve target cycle efficiency. However, high thermal effectiveness (close temperature approaches) is frequently encountered in more conventional offshore applications, too. The picture below refers to a 11MW offshore gas/gas exchanger.

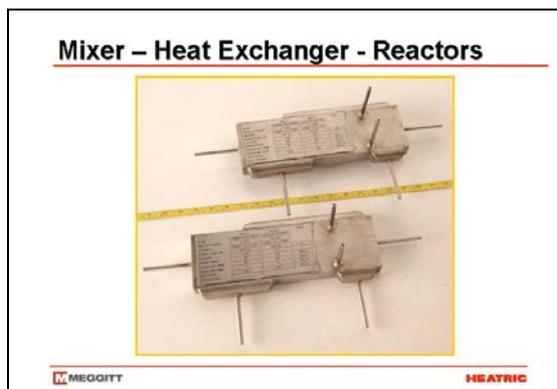


CHEMICAL REACTORS

The potential for microchannel devices as chemical reactors has been widely explored. For many years the concept has been confined to the laboratory bench, but Heatric is now beginning to find increasing commercial interest in a wide range of reactor duties for its Printed Circuit technology, and has coined the acronym **Printed Circuit Reactor (PCR)** to cover these applications.

Mixer-Heat Exchanger-Reactors

By integrating heat exchange, fluid mixing, and reaction into one printed circuit block, the number of components in the system is reduced. More importantly, however, short mixing paths can lead to vastly accelerated reaction, reduced residence times, and thereby improved selectivity and product yields, when compared with traditional stirred tank (batch) reactors. Below are printed circuit units designed to perform mixing, heat exchange, and reaction on a continuous basis.



Heterogeneous Catalytic Processes

A wide variety of different 'macrochannel' reactor concepts have been used in industrial heterogeneous catalytic processes – for example fixed bed, moving bed, fluid bed, and bubble column. Each arrangement has been devised to address specific process requirements, especially temperature control. It is this challenge of temperature control that is of particular interest to us, since in many processes improved temperature control can lead to improved yield and selectivity.

Heatric is developing PCR concepts specifically targeted at heterogeneous catalytic processes. The concepts offer:

- optimum temperature profile for selectivity and conversion;
- minimum catalyst volume;
- minimum risk of catalyst overheating;
- minimum pressure drop;
- an optimal trade-off between capital cost and performance.

Two broad approaches are being pursued: the "In Passage" (IP) Reactor, and the "Multiple Adiabatic Bed" (MAB) Reactor.

In Passage (IP) Reactor. The concept of coating a heat transfer surface with catalyst has been quite widely discussed: for example, a recent study was presented at the 4th International Conference on Process Intensification for the Chemical Industry (Babovic et al., 2002). However, one of the big challenges is how to provide sufficient catalyst surface at reasonable capital cost. The IP PCR, being structurally analogous to a PCHE, offers the desired high surface density, over the full range of operating conditions, at demonstrably competitive cost.

However, perhaps the biggest challenge is the availability of suitable catalysts. Substantially improved catalyst activity is needed if we are to take full advantage of the opportunity offered by a coated passage reactor. Catalyst life and resistance to poisoning or deterioration are also of paramount importance when considering layers only a few microns thick. Whilst these catalyst issues are best addressed by specialists in that field, Heatric is developing and evaluating techniques for applying catalyst coatings to the passages within a PCR, and we believe robust and renewable coatings can be applied in a cost-effective manner.

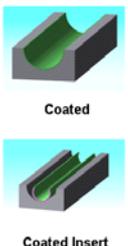
Key benefits of a coated IP PCR include:

- The reactant flow contacting the catalyst surface has no dead-spots or recirculating flows, which commonly compromise selectivity.
- The level of turbulence in the reactant flow can be readily adjusted to minimize gas-phase mass transfer resistances, which would become increasingly important at higher reaction rates.
- Process pressure drop can be readily optimized.
- By skillful application of counter-, cross- and co-flow, the cooling medium flow pattern can be configured to ensure tight control over catalyst temperature profiles.
- PCRs are cost-effectively manufactured in high performance material.
- The PCR structure is inherently small-scale and, in the case of potentially explosive reactants, can be designed to quench any tendency for explosion.
- Pre-heaters and post-coolers may be conveniently close-coupled to the reactor within the same microstructured core, thereby minimizing piping and structure costs.

IP PCR

Catalyst-coated passages offer:

- Outstanding temperature control at the reaction surface
- Opportunity for dramatically increased catalyst activity

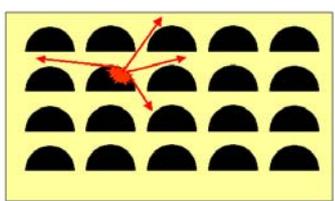


Coated

Coated Insert

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IP PCR



Matrix construction dissipates hot-spots

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Inevitably it will not always be possible to match (or even approximate) the required catalyst surface with the required heat transfer surface. In this case the coated IP PCR risks simply becoming a rather expensive catalyst support, and an alternative approach is needed. A logical alternative is then to decouple the catalyst and heat transfer surfaces.

Whilst this approach may be expedient for certain instances, it clearly imposes limitations on passage geometry and reactor size. However, it should be remembered that there is no reason to confine ourselves to small semicircular passages: ribbon shaped passages are

also possible, and the etched plates may be oriented face-to-face, resulting in a symmetrical cross section – perhaps more suited to certain reactor applications.

An example of a microstructured core illustrating these features is shown in the picture below.

Non-Standard Passage Geometry

- Face-to-face plates
- Certain reactor applications



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Multiple Adiabatic Bed (MAB) Reactor. Where the required catalyst surface area is very large, and substantially exceeds the required heat transfer area, a better balance between capital cost and performance may be achieved by approximating the in-passage reactor with a large number of shallow adiabatic beds, with heat exchange between each bed – the Multiple Adiabatic Bed or MAB PCR.

Hitherto the feasibility of such an approach has been constrained by the cost of successive reactor vessels, heat exchangers, and interconnecting piping. Even in the most sophisticated integrated reactor designs, the number of reaction and heat exchange steps rarely exceeds 3 or 4, since the volume required for conventional heat exchange within a reactor vessel becomes increasingly costly with increasing overall reactor vessel size. However, by making use of the very compact nature of PCHEs it is possible to devise cost-effective reactor layouts with many tens of adiabatic beds, with intermediate heating or cooling between each.

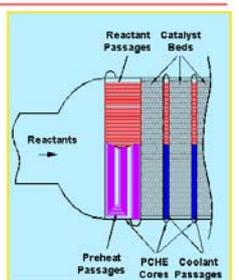
One way of constructing a MAB PCR is to have an array of shallow catalyst beds interposed between thin PCHE panels. Alternatively, a very large number of small adiabatic beds can be incorporated within a single PCR block, together with heat exchange zones to adjust the initial feed temperature, to add or remove heat of reaction between each catalyst bed, and to adjust the product temperature. The heating or cooling medium may simply be a utility stream, or it too can undergo a separate reaction within a separate sequence of catalytic beds.

MAB PCR - The Concept

The MAB PCR consists of alternating:

- Adiabatic catalytic beds and
- Printed Circuit Heat Exchanger (PCHE) panels

The MAB PCR combines only proven technologies



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A demonstration unit has been manufactured to investigate this concept for a petrochemical process. It has 4 catalyst beds, with staged reactant addition and interstage cooling in integral microchannel exchangers. Testing is scheduled for Q1-Q2 2003, in collaboration with a major international oil company.

Petrochemical Processes

- Lab Investigation
- 4 Catalyst Beds
- Inter-stage Cooling
- Reactant Addition
- Separate feed/effluent exchanger




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FUEL CELL SYSTEMS

Heatric is actively extending the range of application of its technologies to include fuel cell systems, with the objective of developing and supplying components suitable for commercially viable fuel cell powered products and hydrogen production.

Hydrocarbon Fuel Reforming

At the time of writing we are engaged in the initial start-up of our first prototype fuel processor based around steam methane reforming. This initial 'proof-of-concept' features MAB PCR technology, and was described last year at the AIChE Spring Meeting (Johnston and Haynes, 2002). The remarkable feature of this prototype design is the combination of 27 catalyst beds and 20 heat exchangers into 5 compact and simple to manufacture microchannel blocks.

Steam Methane Reforming - Demonstration

- 2 x pre-reforming stages
- 9 x reforming stages
- catalytic combustion




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Steam Methane Reforming - Demonstration

- 3 x pre-reforming stages
- MTS and LTS
- CO PrOx




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Work on an initial prototype gasoline steam reformer is currently underway, and we anticipate rapid design development based on our initial test results.

Vaporisers

Numerous different process schemes have been put forward for the so-called "balance of plant" associated with fuel cells, but many feature liquid fuel vaporisers and steam generators. This duty is often particularly challenging when the heating medium is reformer effluent or combustion gas, resulting in a very large temperature difference between the cold (vaporising) and hot streams. When considered together with the inevitable thermal transients associated with start-up, shut-down and load fluctuations, few of the vaporiser designs currently available to the balance of plant designer can economically satisfy the requirement for reliability and long service life.

PCHEs can offer the mechanical integrity and high performance materials of construction needed for demanding applications, and Heatric is engaged in the development of specific designs to meet the needs of several users. PCHEs such as the one shown below have been supplied in combined vaporising and superheating duty at temperatures around 600°C.

Vaporiser For Stationary Reforming Application

- Power Density of 10 W/cm³
- Less than 15 kPa pressure drops
- 10 barg design pressure
- 600°C superheated vapour

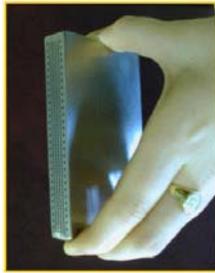


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Certain applications have additional size constraints. The very compact nature of PCHEs enables us to devise high power density vaporisers, such as the steam raising device shown below.

Vaporiser for Automotive Fuel Cell System

- Compact Vaporizer Core
- Heated by flue gas
- Power density 50 W/cm³
- Power density 10 W/g
- 300°C superheated vapour



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Microscale Manufacturing

- Alliance with IMM, Mainz
- Successful demonstration of "micro" scale manufacture
- Total weight of 200 g



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HYDRAULIC DEVICES

We have hitherto devoted our attention to heat transfer and chemical reaction. However, other devices may also put the characteristics of microchannels to good use, including internal components for pressure reducing valves.

An illustrative slice from a typical control valve trim is shown in the following picture.

Hydraulic Devices

- Pressure reducing devices



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We aim to build on this initial success with market-ready products later this year.

CONCLUSIONS

The construction method for PCHEs and PCR is remarkably flexible: these type of industrial microchannel devices have been supplied in sizes ranging from 100 tonnes down to something as light as 200 gram.

Industrial microchannel devices size range



Offshore (100 tonnes)



Offplanet (5 kg)



IMM Cross Flow Exchanger (0.2 kg)

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TWO HEADS ARE BETTER THAN ONE!

Several other research and development institutions have devoted considerable efforts to devising and evaluating a variety of microchannel devices. Heatric has forged an alliance with the Institut für Microtechnik Mainz (IMM), one of the leading German institutions working in this subject area. Our alliance is complementary, rather than collaborative, and is aimed at progressing the economical mass manufacture of IMM designed micro devices. The first steps taken together were aimed at demonstrating the techniques normally used to manufacture microchannel cores weighing several tonnes could be successfully applied to items weighing only a few grams. The result of this successful first trial is shown below.

Heatric's Microchannel Devices



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We believe demand for industrial microchannel devices will continue to evolve, and we are actively positioning ourselves to apply our existing core expertise to new market and innovate solutions for industries

REFERENCES

Babovic, M., Gough, A., Leveson, P. and Ramshaw, C., 2002, Catalytic Plate Reactors for Endo- and Exothermic Reactions, *4th International Conference on Process Intensification for the Chemical Industry*, Bruges.

Johnston, A., and Haynes, B., 2002, Heatric Steam Reforming Technology, *2nd Topical Conference on Natural Gas Utilisation*, AIChE 2002 Spring National Meeting, New Orleans.