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Heat Transfer Challenges In Fuel Cell Systems

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Abstract

Every fuel cell system integrator faces their own individual challenges addressing the ever-present issue of heat management, dependent on fuel cell type as well as the hydrogen source (fuel) and fuel processing route. Most fuel cell systems feature hydrocarbon gas and steam as reactants feeding a reformer. Heatric's established expertise in compact heat exchange naturally leads us to examine these opportunities more closely.

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. PCHEs are matrices formed by diffusion bonding together plates into which fluid flow passages 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. With headers and nozzles attached to the PCHE cores, the complete 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 austenitic stainless steels, suitable for design temperatures up to 800°C. Higher design temperatures (>900°C) are possible with alloys such as Incoloy 800HT.

Heatric's expertise may be beneficial to several aspects of fuel cell system integration. The feasibility of incorporating very large numbers of unit operations into a single diffusion bonded block was described by Tony Johnston and Brian Haynes at the AIChE 2002 Spring Meeting. However, this paper addresses another aspect – the design of vaporisers (fuel or water) heated by very hot gas streams. Whilst the principles apply to, fuel or water vaporisation, heated by reformer effluent or fuel cell exhaust gases, our paper focuses on steam raising. The steam generated will be either fully saturated or superheated as reactant feed to a reformer. The hot gas is typically between 500 to 900°C. As a result, robust and high integrity exchangers are required.

For fuel cell vehicle applications, the heat transfer system must also be lightweight, compact and comprise a minimum of components. When it comes to operation, the heat exchanger must utilise the allowable pressure drop efficiently, and must have fast response, with minimal fluid remaining in the exchanger. All these considerations call for the application of compact heat exchangers because of their small fluid inventory.

Heatric has investigated using single PCHE to vaporise the water from ambient temperature to superheated steam. Experimental results of performance, response and fuel remaining in exchanger tests are reported. All of these tests showed a satisfactory outcome. A power density of around 50 W/cm^3 and 10 W/g has been demonstrated for a typical fuel cell application. Two modes of testing the life of the vaporiser have been carried and are reported here. Several suggestions are proposed in this paper to extend the life of the vaporiser.

Introduction

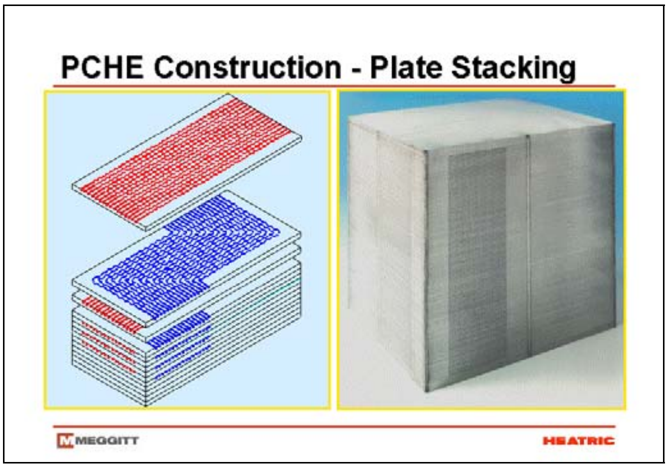
Our intention in this paper is to examine some of the challenges in fuel cell "balance of plant" heat transfer, to provide an update on Heatric's technologies, and to consider what these technologies have to offer in fuel cell systems.

The Printed Circuit Heat Exchanger (PCHE) is an established compact 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. It soon became apparent that one of the biggest potential markets for the new technology was in offshore gas processing, where space and weight savings are at a premium.

Following Heatric's move to the UK in 1989, PCHEs rapidly gained acceptance in the offshore industry. Many thousands of tonnes of compact 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, and caustic soda plants. More recently, fuel processing and other balance of plant applications for fuel cell systems have emerged as suitable applications for PCHE technology.

Printed Circuit Technology

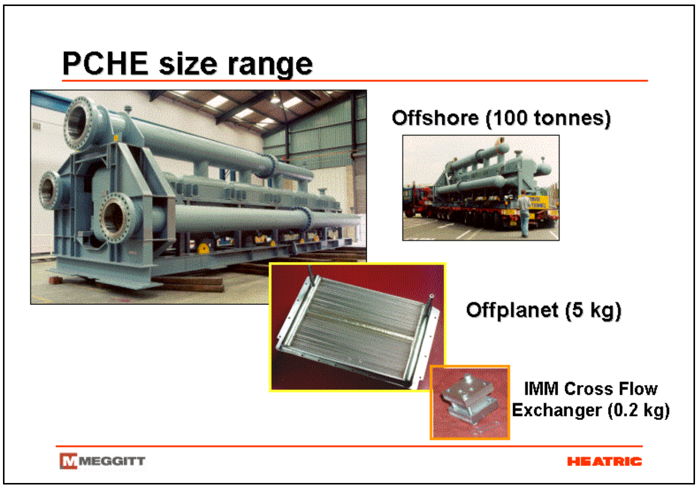
The compact core of a PCHE is constructed by chemically milling flow passages into flat metal plates, and then stacking and diffusion bonding the plates together into a single block. The chemical milling technique is analogous to that used for the manufacture of electronic printed circuit boards, and this gave 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.

If necessary, 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.

The construction method is remarkably flexible: PCHEs have been supplied in sizes ranging from 100 tonnes down to something as light as 200 gram. Two laptop-size PCHEs are even to be found orbiting the Earth in the International Space Station!

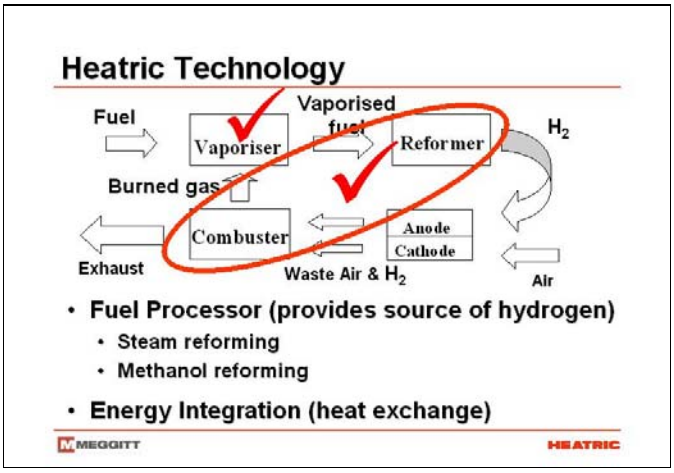


Heatric Technology in Fuel Cell Systems

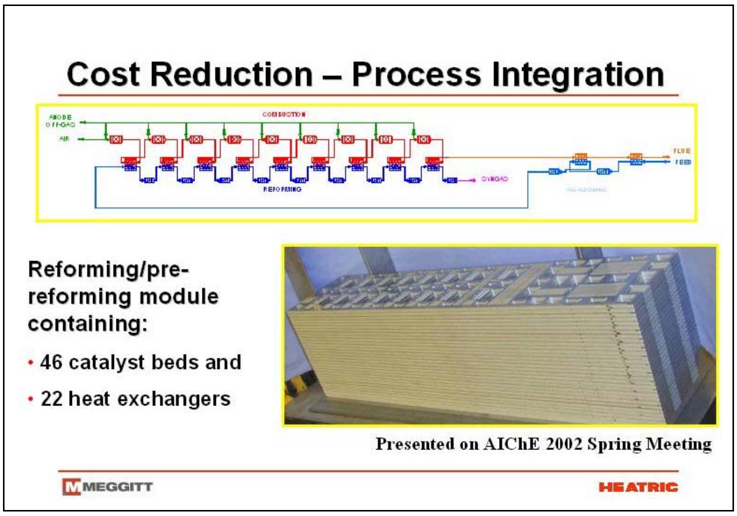
Our ability to provide a unique solution to compact heat transfer with PCHEs, and our extensive experience in the current market, lead us naturally to extend our expertise into the fuel cell arena.

We believe Heatric technology offers benefits in two fuel cell system applications:

1. Compact Fuel Processors
2. Compact Vaporisers

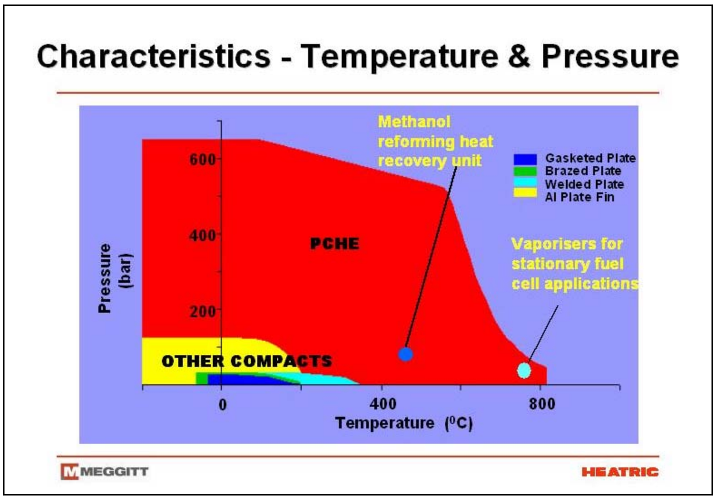


We presented a concept incorporating 20 reactions stages and 11 heat exchangers into a single reforming/pre-reforming module at the AIChE 2002 Spring Meeting (Johnston and Haynes, 2002). This novel and innovative application of Printed Circuit Technology permits the number of individual components to be dramatically reduced, with follow-on manufacturing cost savings. The same principle can be applied to methanol reforming (Johnston et al. 2001).



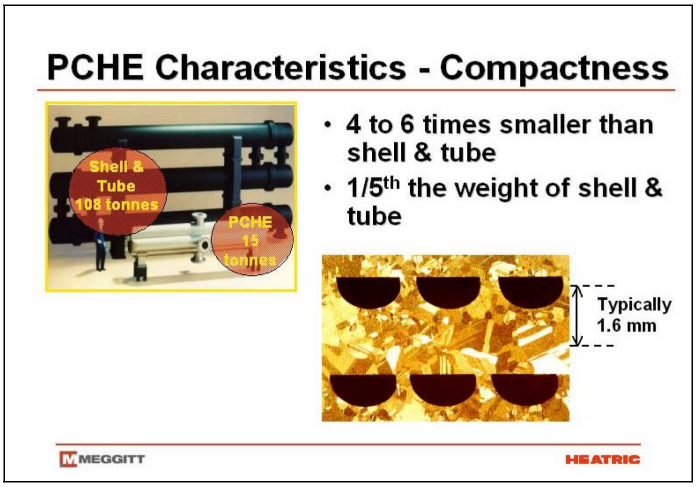
However, we have also considered another aspect – the design of vaporisers (fuel or water) heated by very hot gas streams. Whilst the principles apply equally to fuel or water vaporisation, heated by reformer effluent or fuel cell exhaust gases, we shall focuses on steam raising. The steam generated will be either fully saturated or superheated as reactant feed to a reformer. The hot gas is typically between 500°C and 900°C. As a result, robust and high integrity exchangers are required.

PCHEs are well suited to this type of application because of their temperature and pressure capability. Austenitic stainless steel PCHEs are suitable for design temperature up to 815°C while the use of Incoloy 800HT permits a design temperature in excess of 900°C. PCHEs have, therefore, found application in both methanol reforming and hydrocarbon reforming (steam or ATR) systems.

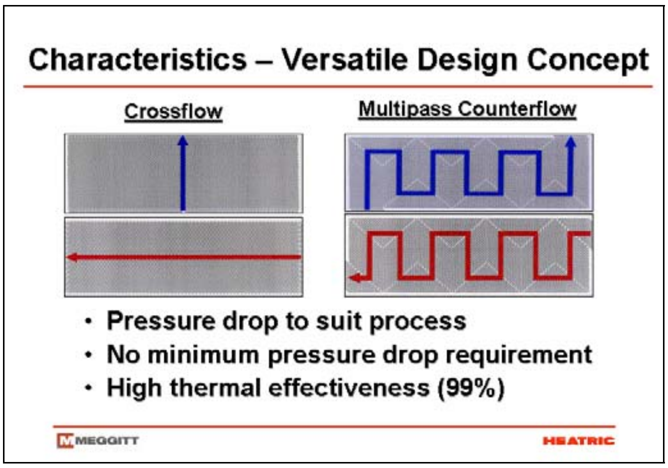


For fuel cell vehicle applications, the heat transfer system must also be lightweight, as well as compact, and comprise a minimum number of components. With headers and nozzles attached to the PCHE cores, the complete heat exchangers are highly compact, typically comprising about one-fifth the size and weight of conventional heat exchangers for the same thermal duty and pressure drops. This is attributable to:

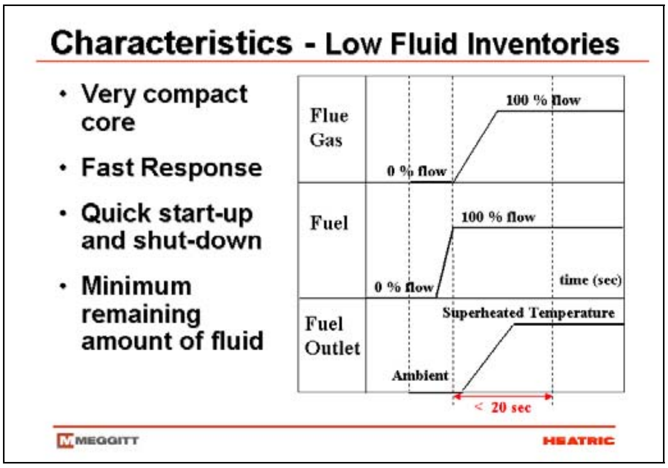
- very high surface area density,
- enhanced heat transfer coefficients,
- very small stream-to-stream thermal resistance (wall thickness), and
- potentially near-perfect counter current flow.



When it comes to operation in the fuel cell system, the heat exchanger must utilise the allowable pressure drop efficiently. This can easily be done with PCHEs because the design flexibility of Printed Circuit Technology permits a flow path in the exchanger to be devised to suit the system pressure drop. This is an attractive point when it comes to the power efficiency of the entire fuel cell system.

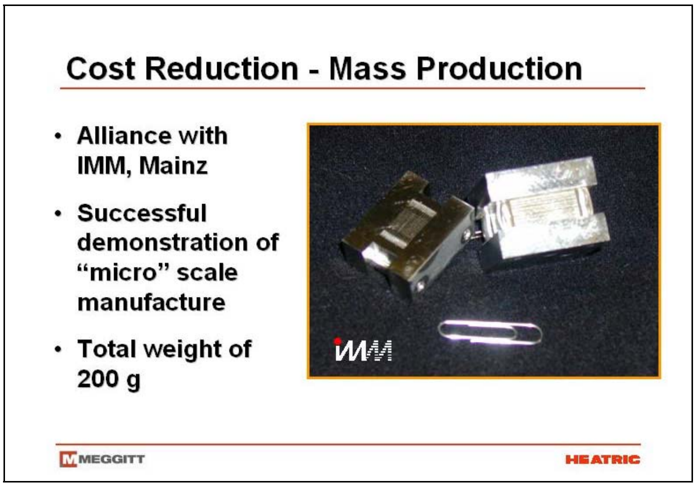


Further operational requirements in a fuel cell system are fast response, start-up and shut down, with minimal fluid remaining in the exchanger. All these considerations call for the application of compact heat exchangers, such as PCHEs, because of their small fluid inventory. In one of our typical performance tests, it only takes a matter of seconds to produce sufficient steam to meet process requirements.



For fuel cell technology to be commercially viable, the system cost must obviously be affordable. Heatric's proven manufacturing techniques are readily applicable to mass production of 'micro-scale' vaporiser core.

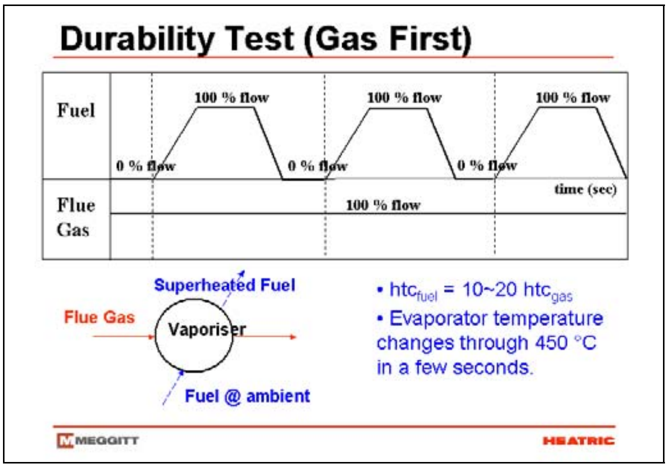
This point has been successfully demonstrated in collaboration with IMM, (Mainz, Germany). The exchanger shown in the picture below weighs only 200 grams! Continuing collaboration is aimed at commercial supply of commodity micro (heat exchange) devices in the near term.



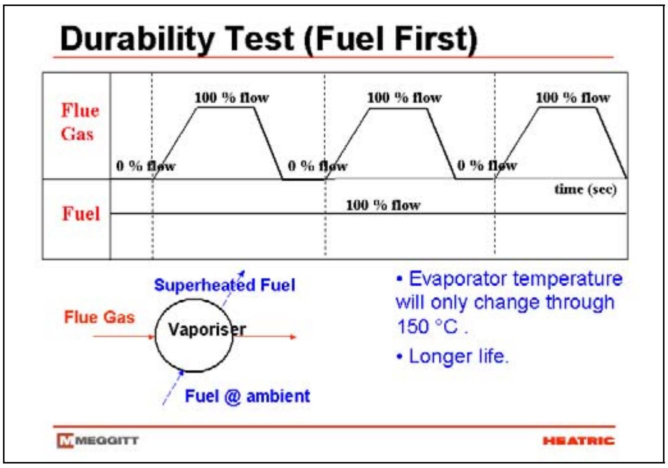
Heat Transfer Challenges

To start up a liquid fuel vaporiser, one will have a choice of either establishing the flue gas flow first or the fuel flow first. Any equipment downstream of the vaporiser will experience some temperature change. By repeatedly starting-up and shutting-down the fuel cell system, the components in the system will experience temperature cycles in this period. This thermal cycling presents a potential challenge to the service life of many system components – including the vaporiser itself.

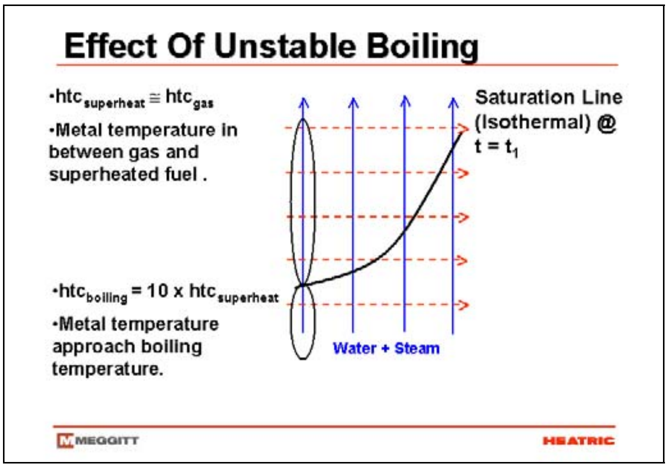
The vaporiser in particular, when operated in the 'hot gas-first' mode, will experience a temperature change of, say 450°C, in a few seconds. This is because the heat transfer coefficient of the fuel is normally ten to twenty times higher than the hot gas.



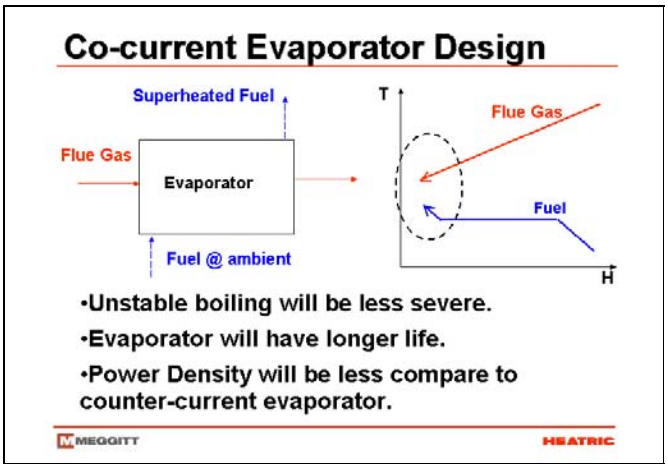
However, if the operational mode is reversed, the vaporiser will see a smaller temperature change, because the metal temperature will tend towards the temperature of the stream with the higher heat transfer coefficient. As a result, a vaporiser operated in this mode would be expected to have a longer service life than the one operated in the 'hot gas-first' mode.



Another issue concerning temperature change within the vaporiser is unstable boiling. The nature of unstable boiling has been well reported: the main design challenge is to overcome the rate of temperature change caused by an unstable saturation line.



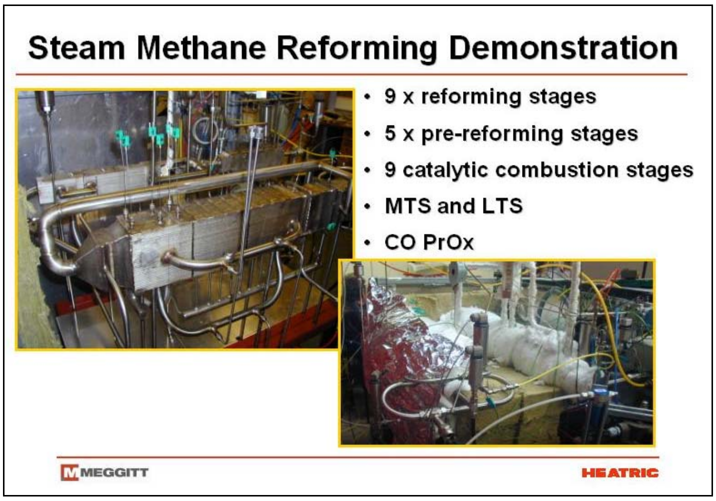
One way to overcome this problem is to design the vaporiser to operate co-currently. In this way the maximum temperature change that may be caused by unstable boiling is minimised.



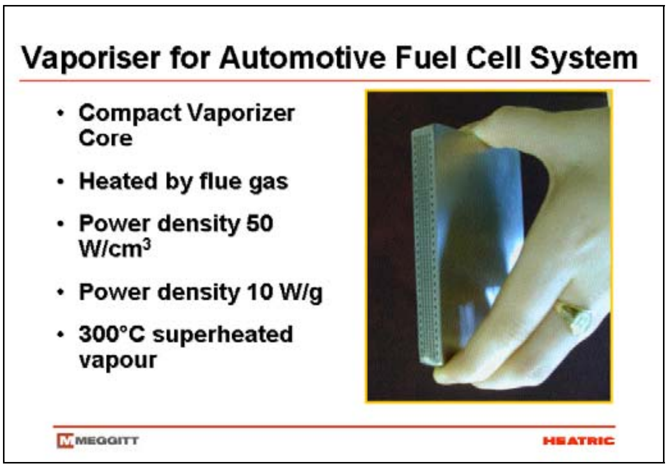
Current Fuel Cell Activities

Heatric is actively engaged in extending its fuel cell system expertise, with the objective of developing and supplying components suitable for commercially viable fuel cell systems.

At the time of writing we are engaged in demonstrating the 'proof-of-concept' of using Heatric's Multiple Adiabatic Bed PCR technology in the steam methane reforming process, as described last year (Johnston and Haynes, 2002).



With the very compact nature of PCHEs, we are able to produce high power density vaporisers for a typical steam raising process for a fuel cell application.



Lastly, we are involved in developing the necessary techniques to protect against coking and high temperature corrosion mechanisms commonly encountered in the reforming process.

References

(1) Johnston, A.M., and Haynes, B., *Heatric Steam Reforming Technology*, AIChE Spring Annual Meeting 2002.

(2) Johnston, A.M., Levy, W., Rumbold, S.O., *Application of PCHE Technology within Heterogeneous Catalytic Reactors*, AIChE Annual Meeting 2001.