Proceedings of $SCO_2$ Power Cycle Symposium 2011
University of Colorado at Boulder - University Memorial Center, CO, May 24-25, 2011
Paper xxx

# Impact of Mechanical Design Issues on Printed Circuit Heat Exchangers

Renaud Le Pierres, David Southall, Stephen Osborne
Heatric Division of Meggitt (UK) Ltd.
*46 Holton Road, Holton Heath, Poole, Dorset BH16 6lT, United Kingdom.*
*Tel: +44 (0) 1202 627000 , Fax:+44 (0) 1202 632299 , Email: Renaud.lepierres@meggitt.com*

**Abstract** - *Power conversion cycle efficiency is a key factor in the design of new generations of power plants irrespective of the heat source. In response to increasingly demanding emission regulations throughout the world there is now a drive to improve on the existing cycles, a drive which is supported by public opinion. This has resulted in the promotion of several new concepts for power conversion cycles. Of these new cycles the Supercritical Carbon Dioxide (SCO2) Brayton cycle is one of the most promising. Over the last few years many SCO2 brayton cycles have been designed to operate at pressures ranging between 20 MPa and 30 Mpa and with turbine inlet temperature between 500 °C and 600 °C. In order to obtain higher efficiencies wide use is made of heat exchangers and recuperators. To achieve efficiences of 45% and above intermediate heat exchangers and recuperators must be able to provide very close temperature approaches while withstanding demanding operating pressure and temperature combinations that require very high mechanical integrity.*

*Printed Circuit Heat Exchangers (PCHEs) have been used on the Barber-Nicholls/Sandia National Laboratory test loop for the cooler, low temperature recuperator and a high temperature recuperator applications. The compact diffusion bonded PCHE offers many advantages which contribute to the performance, safety and viability of the SCO2 brayton cycle. The use of diffusion bonded construction delivers high mechanical integrity. Their high surface area per unit volume allows a closer temperature approach in a more compact space envelope compared to an equivalent Shell and Tube heat exchanger. The PCHE can be manufactured with a wide range of materials including high grade alloys which are useful for higher temperature or pressure applications where the use of SS316L is restricted. The PCHE has great flexibility to including variable angles and flow paths to increase heat exchange while balancing pressure drop as well as the potential for multi-stream heat exchange.*

*Many papers have been published on the PCHE for use in power generation by various entities other than Heatric, predominently for nuclear applications associated with Gen IV cycles. A lot of these papers have been built on assumptions resulting from interpretation or reverse engineering of public domain information provided by Heatric who have been designing and manufacturing PCHEs for more than 25 years. This has resulted in many papers with various, often contradictory, claims about PCHE performance which ignore the impact of mechanical design issues on the design of PCHEs.*

*The aim of this paper is to review some of these assumptions in order to clarify and correct them, as well as to introduce some of the mechanical design considerations and challenges which significantly affect the final geometry of the PCHE being engineered condition.*

## I. INTRODUCTION

Heatric[1] has been manufacturing the Printed Circuit Heat Exchanger (PCHE) for more than 25 years, used predominantly in the Upstream Oil and Gas market. There are more than 1,000 units sold to date, some of them still in operation after nearly a quarter of a century. As a compact heat exchanger able to operate both at high pressures and temperatures with very close temperature approach, the technology has attracted the attention of many design engineers and research laboratories involved in power conversion cycles development, including SCO2 Brayton Cycles. Heatric products offer unique advantages of close temperature approach combined with high temperature and pressure while the compactness of the unit is consistent with the rest of the SCO2 power plant and minimize size and cost compared to other heat exchangers. The need for more efficient power conversion cycles in light of continuous forecasts in energy consumption and price increase lead to many design studies and papers about enabling technologies able to withstand the challenging process conditions. However most of these papers discussed the optimization of thermal and hydraulic process conditions in order to achieve higher efficiency. Thus many topics were discussed referring to keywords like *surface density* and *free-flow area*, to assess rough volume size of heat exchangers to achieve thermal and hydraulics requirements. While this approach can provide an indicative sizing in conventional duties with relatively low temperatures and pressures combinations, experience shows it is not so successful in much more challenging processes as the mechanical design becomes a major factor in defining the heat exchanger size. While this paper will only cover the PCHE, Heatric do manufacture Formed Plate Heat Exchangers (FPHEs), and Hybrid Heat Exchangers (H²Xs) and will be bound by similar constraints as with the PCHE (Fig. 1).

Fig. 1. PCHE, FPHE and H²X block sections.

## II. UNDERSTANDING THE PCHE BASIC GEOMETRY

In order to understand the mechanical design of a PCHE, we need to clarify how it is made and what the internal geometry is. The following sentence, now well known and used in so many papers, gives a broad but true definition about the product:

The Printed Circuit Heat Exchangers (PCHEs) consist of flat metal plates (Fig. 2) into which fluid flow channels are chemically etched, before being joined by Diffusion Bonding to make a heat exchanger block (Fig. 2) to which headers and nozzles may be welded.

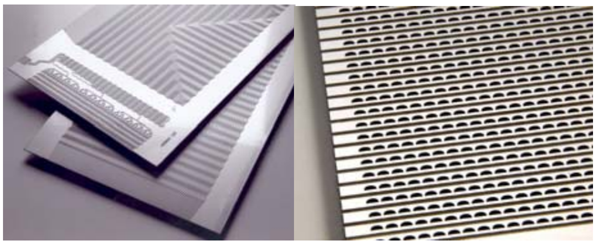

Fig. 2. Example of PCHE etched plates and section of PCHE block.

We will now introduce a few keywords which are used in the mechanical design of a typical 1E 1S PCHE block (Fig. 3):

***Channel**:*

The PCHE internals are mostly made of near semi-circular channels, with etch depth varying from 0.1 mm up to 2.5 mm (thus channel width will vary from 0.2 mm up to 5 mm).

***Ridge**:*

Ridges are the unmilled regions <u>between</u> the channels. Ridge thickness will be based on design pressure and influenced by the channel etch depth.

***Wall**:*

The channel walls are the region <u>above</u> and <u>below</u> the channel. The walls thickness will be influenced by the channel width.

***Side and End Margin:***

Margins are the non etched areas on the plates, with <u>Side Margins running parallel to the main flow direction</u> and <u>end margins being perpendicular to the flow directions.</u> Note that these will become part of the solid sections used to weld headers onto the block and will be influenced by the headers thickness.

***Block End:***

The block ends are the solid areas at the top and bottom of the diffusion bonded block. Note that these will have the same constrains as the side and end margins.

.

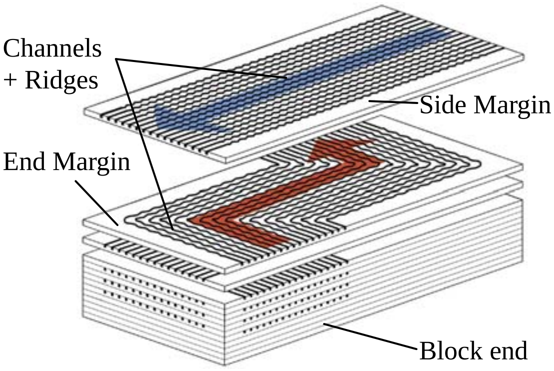

Fig. 3. 1E 1S Layout.

PCHE blocks will usually have Headers, Nozzles and Flanges welded to the block to constitute the whole of the heat exchanger. To date Heatric manufactures diffusion bonded blocks with an individual size of 1.5 m long by 0.6 m wide x 0.6 m stack. Several blocks can be welded together in order to achieve a bigger heat transfer area in a single welded assembly$^2$.

## III. PCHE MISCONCEPTIONS

As previously stated PCHEs are diffusion bonded heat exchangers. Diffusion bonding[1] is a solid state joining process, similar to forge welding, involving pressure to bring surfaces into intimate contact and heat to promote grain growth through the interface (Fig. 4).

The process results in a strong, compact, all-metal heat exchanger cores with parent metal properties providing safety through its high integrity. As with welded frame-plate heat exchangers, the product cannot be disassembled without destruction of the cores in order to reveal internals once it is fully manufactured.

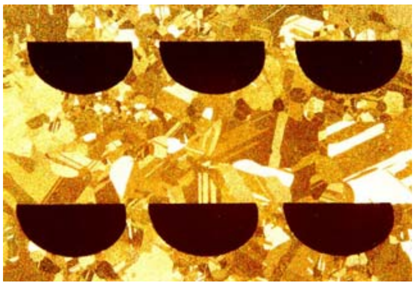

Fig. 4. Micrograph of a PCHE section in the crossflow region.

Several papers refers to the PCHE and the analysis of its performance using mostly public material or empirical data gathered from test of mock-ups, with some mock-ups sectioned in order to reverse engineer them. However several assumptions are incorrect:

*III.A. PCHE Channels*

A) Straight or Wavy:

PCHE channels can be either straight or wavy angles (similar to Herringbone fins used in fin plate heat exchangers) depending on the process requirements (Fig. 5). The flexibility of the etching process means they can use any angle increments (1° or less) over a wide range, unlike fins which are usually manufactured at set angles.

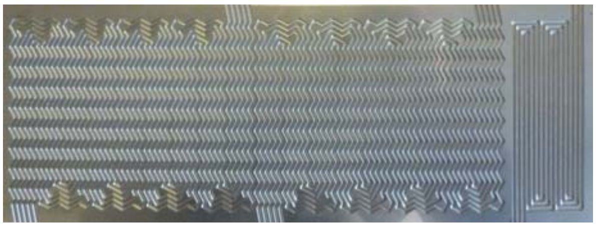

Fig. 5. Multistream plate with Straight and Wavy channels.

B) Parallel or Offset:

A few presentations[3] referred to channels arrangement inside a PCHE block, extrapolated from photos of section of PCHE blocks, describing two possible configurations for a PCHE being either parallel or offset. The resulting assumption was that PCHE are designed using either one or the other configurations.

Once plates are stacked on top of each others and depending on the flow path each plates is using, a section of the block may show an alignment different from another section of the block. The figure 7 shows using two wavy channels plate for cold and hot can results in parallel channels alignment on the left section and staggered channels alignments on the right section in the same block. (Fig. 6).

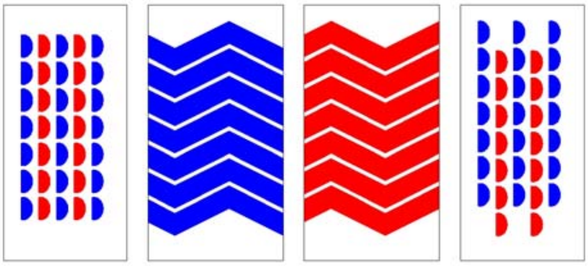

Fig. 6. Parallel and Offset configurations resulting from stacking of plates.

*III.B. Performance correlations:*

As PCHE grew in popularity due to the benefits in performance, compactness and integrity it would bring to many power conversion cycles in Gen IV, many nuclear conceptual PCHEs were developed from 2006, with papers comparing performances of new concepts with Heatric PCHE.

A paper[4] released prepared by K. Nikitin, Y. Kato and T. Ishizuka from Tokyo Institute of Technology compared the PCHE channels to the S-Fins. The picture below (Fig. 7) shows an example of a Heatric channel compared with the given description of the Heatric channel in the paper.

Fig. 7. Heatric PCHE channels (left) – T.I.T. claim for PCHE channels (right).

A direct visual comparison shows that the angle claimed by T.I.T. is much more acute and the channel flow length between directional changes is much longer.

The paper gave the following correlation:

$$Nu = (0.0729 \pm 0.0276) \cdot \mathrm{Re}^{0.717 \pm 0.041} \quad \text{eqn. (1)}$$

$$(3000 \le \mathrm{Re} \le 20600; 0.76 \le \mathrm{Pr} \le 1.04)$$

$$f = (1.462 \pm 0.015) \cdot \mathrm{Re}^{-0.112 \pm 0.01} \qquad \text{eqn. (2)}$$

$$(3000 \le \mathrm{Re} \le 20600)$$

Colburn j factor for heat transfer was evaluated.

$$j = \frac{Nu}{\mathrm{Re} \cdot \mathrm{Pr}^{1/3}} \quad \text{eqn. (3)}$$

The graphs below show the discrepancy between Heatric channels and T.I.T. assessment:

- Dark blue line: Heatric straight channel
- Orange line: Heatric low angle channel
- Red line: Heatric high angle channel
- Red hatch: Heatric domain range

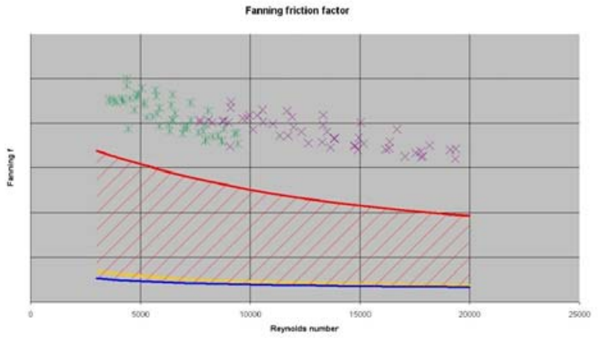

Fig. 8. Comparison of Fanning factors between Heatric and T.I.T. correlations.

The green and purple scatter are the T.I.T. correlation results

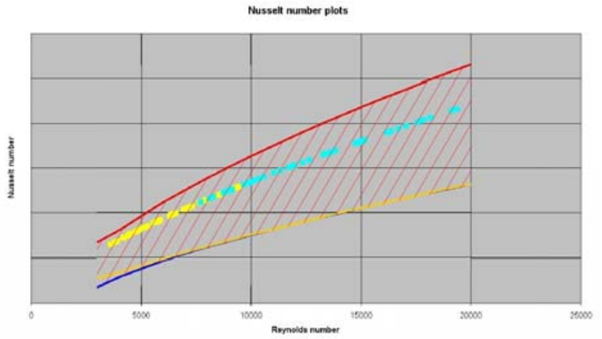

Fig. 9. Comparison of Nusselts numbers between Heatric and T.I.T. correlations.

The yellow and light blue scatter are the T.I.T. correlation results.

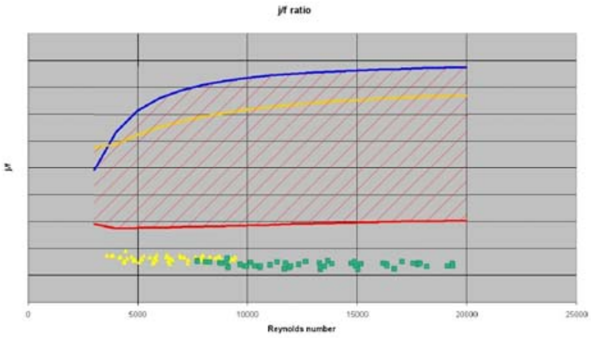

Fig. 10. Comparison of f/j ratio between Heatric and T.I.T. correlations.

The yellow and green scatter are the T.I.T. correlation results.

From these results we can see that the wavy channel T.I.T. provided a correlation has much higher fanning f friction factors (Fig. 8) compared to any of the channels used in Heatric heat exchangers while Nusselt numbers are below the highest Heatric channel angle (Fig. 9). This result in a f/j ratio well below any of the Heatric channel used (Fig. 10). Such approach makes it easier to introduce new surface geometry supposedly more efficient than the PCHE channels.

## III. PCHE MECHANICAL DESIGN

PCHEs and other Heatric heat exchangers can be used in a wide range of temperatures and pressures conditions as per the following chart:

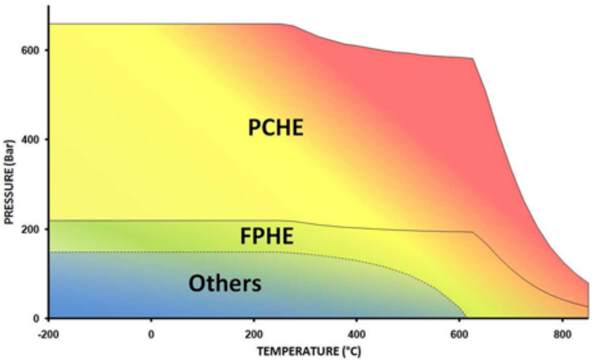

Fig. 11. Temperature and pressure capabilities

Heat exchanger design is an iterative process in order to achieve the specified duty while sustaining the process pressures and temperatures.

While the thermo-hydraulic design of the PCHE will be driven by the channel cross section, the wall thickness between each streams acting as the primary heat transfer, the mechanical design of the PCHE block involves sizing to withstand the design pressure at the design temperature of the following:

- Ridge thickness (influenced by the Channel depth and the sheet gauge);
- Wall thickness (influenced by the Channel width);
- Side Margins (influenced by the end headers thickness);
- End Margins (influenced by the side header thickness);
- Block ends (influenced by the thicker of the headers);

For the purpose of this paper, we will only concentrate of the PCHE block and the first pressure retaining component welded to it.

A) PCHE Block Design:

As described in section II, a PCHE block is made of channel internals surrounded by solid regions to where headers are welded onto. The channel configuration is that of a rectangular vessel with multiple stay plates as illustrated in Fig. 12. The side margins are the long side plates, the unmilled regions at the plate edges are the wall, and the unmilled regions between channels (the ridges) are the stay plates.

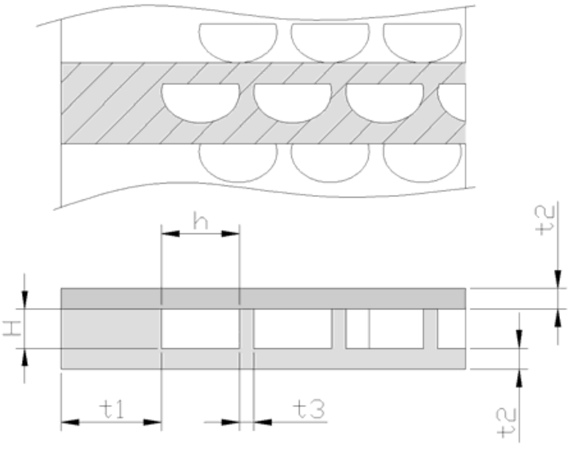

Fig. 12. Simplification of the block geometry for mechanical design.

With:

h = channel width

H = channel depth

t1 = edge width

t2 = wall thickness

t3 = ridge width

- side margin thickness t1: side margins will be will be based on membrane (Sm) and bending (Sb) stress formulae in order to find the total stress (St). These are assessed against the design stress S at a given joint factor E. For the diffusion bonded block, the joint factor is 0.7. The membrane stress must remain below SE, and the total stress must remain below 1.5SE by these rules.

$$S_m = \frac{Ph}{2t_1} \qquad \text{(ASME 13-9(13) for } K \to 0\text{)}$$

$$(S_b)_N = \left(\frac{Pc}{24I_1}\right)\left(2h^2 - 3H^2\right)$$

(ASME 13-9(16) for $K \to 0$)

Where $I_1 = \frac{t_1^3}{12}$ & $c = \frac{t_1}{2}$

$$(S_b)_Q = \frac{Ph^2}{12I_1} \qquad \text{(ASME 13-9(17) for } K \to 0\text{)}$$

$$S_T = S_m + S_b$$

With:

P = design Pressure

S = design stress

E = joint factor

c = distance from neutral axis to extreme fiber

I = moment of inertia

K = vessel parameter (tends to zero as $I_1 >> I_2$)

The wall thickness t2 will be based on same principle with different formulae.

$$S_m = \frac{PH}{2t_2} \qquad \text{(ASME 13-9(14))}$$

$$(S_b)_{M,Q} = \frac{Ph^2c}{12I_2}$$

(ASME 13-9(18)&(19) for $K \to 0$)

Where $I_2 = \frac{t_2^3}{12}$ & $c = \frac{t_2}{2}$

$$S_T = S_m + S_b$$

The wall thickness t3 will be based on the same principle with different formulae due to the same pressure being applied on both side of the ridge:

$$S_m = \frac{Ph}{t_3} \qquad \text{(ASME 13-9(15) for } K \to 0\text{)}$$

$$S_b = 0.0MPa$$

$$S_T = S_m + S_b$$

The configuration considers only the internal pressure in one layer of the block and considers the pressure in the adjacent layers to be zero gauge. No differential pressure design is considered by default in the PCHE block.

Due to this approach, the short side plate or unetched sections underneath all channels in the PCHE block must remain the same thickness (t2).

When designing heat exchanger the tendency is to increase the free-flow area by increasing the channel size. However from the calculations above, any increase in channel size will results in an increase in adjacent walls and ridges. This added to tolerances increasing with size will result in a reduced free-flow area and a reduction of the heat transfer surface density.

B) Headers design:

The configuration is equivalent to a cylindrical vessel with a diametral staying member (this member being the block) as illustrated in ASME Fig. 13.2(c)

$$R = 0.5(D_h - 2t_1)$$

$$S_m = \frac{PR}{t1}$$

$$S_b = 0.357(\frac{c}{I})(Pt_1{}^2)$$

$$S_T = S_m + S_b$$

With:

P = design pressure

S = design stress for joint

E = header/block joint effectiveness

Dh = header outer diameter

T1 = header run thickness

R = header inner radius

c = distance from neutral axis to extreme fiber

I = moment of inertia

It is worth noting that the header thickness is driven mostly by the membrane stress. Given the membrane stress formulae, header thickness can rapidly increase with increase in diameter leading to excessive thickness and an equivalent reduction in the internal volume of the PCHE because side and end margin sizes must increase for header attachment purposes in order to accommodate for the welding of the headers to the block.

For very high pressure, rolled headers may not be viable due to the required thickness to achieve the mechanical integrity requirements. These very high pressure units can be handled with one configuration often used by Heatric and facilitated by the diffusion bonding process: the ported or semi-ported PCHE.

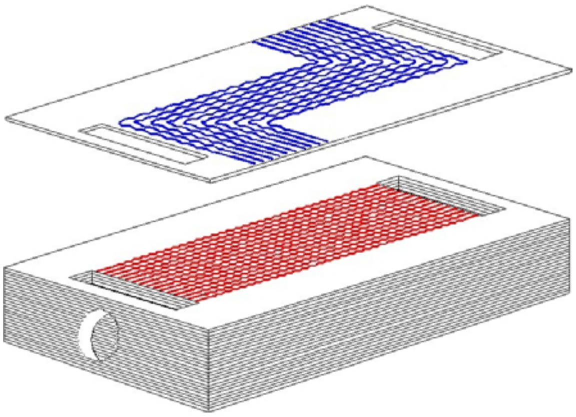

Fig. 13. Semi-ported.

In this configuration, the header is integrated in the plate during the chemical etching process allowing non standard thickness compared to headers (i.e. when thickness prevent rolling and requires forging or machining. Furthermore, this configuration offers the advantage to reduce the overall length of the unit where space is a constraint as the header is flat. The other stream can be a lower pressure unit with a header welded to the block. A ported design will have both sides with etched out headers.

PCHEs can adopt various configurations taking advantages of the etching and diffusion bonding process to create geometries difficult for other technologies to achieve[5,] like the platelet configuration (Fig. 14) where a ported PCHE is designed to operate in pure counter-flow.

In this configuration, the hot fluid (in red in Fig. 14) flows from one inlet port to the opposite outlet port, while the cold fluid (in blue in Fig. 14) flows from the opposite adjacent outlet port making the counter-flow area larger due to the compactness of the port design.

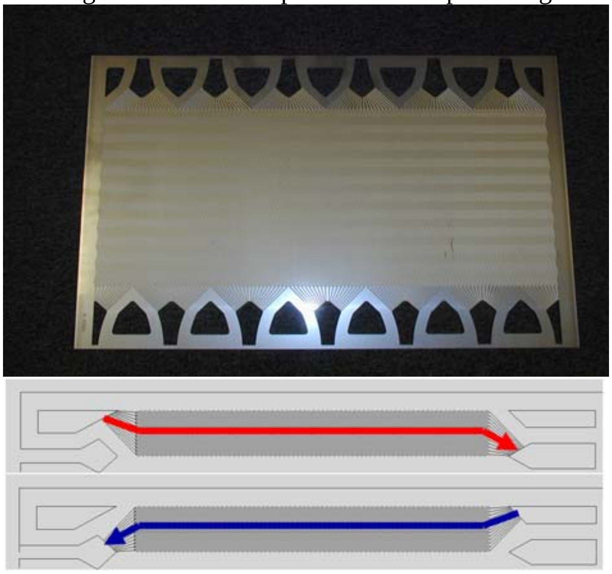

Fig. 14. Semi-ported.

## IV. CONCLUSIONS

Despite a long history of PCHE supplied by Heatric, there are still many misunderstanding and misconception about the technology leading to incorrect claims and publications. The PCHE has been introduced in more details and clarifications have been made to correct some of the most common misconception in the technology.

Furthermore most of the papers released to date have always approach the thermal and hydraulic design of the PCHE rather than the mechanical design which has a greater impact especially when considering high temperature and pressures duties.

Heatric exchange technology will make a significant contribution to SCO2 power cycle. Their ability to operate with close temperature approach and a high pressure and temperature make them ideal for SCO2 due to the compactness of the design giving cost and weight savings for other components of the SCO2 power plant.

## REFERENCES

1. Heatric website: www.heatric.com
2. Diffusion Bonding in Compact Heat Exchangers, D. Southall (Heatric), SCCO2 Power Cycle Symposium 2009
3. Effect of Channel Configurations for Tritium Transfer in Printed Circuit Heat Exchangers, C. Oh (INL), ICAPP 2009
4. Experimental thermal-hydraulics comparison of microchannel heat exchangers with zigzag channels and s-shaped fins for gas turbine reactor, Y. Kato (TIT), ICONE 15
5. Innovative Compact Heat Exchangers, D. Southall (Heatric), ICAPP 2010