THE DEVELOPMENT OF HIGH EFFICIENCY HEAT EXCHANGERS FOR HELIUM GAS COOLED REACTORS. (PAPER NO. 3213)

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1. ABSTRACT.

This paper considers the requirements and development of a suitable heat exchanger for both recuperator and intermediate heat exchanger HTR applications.

For power generation there is an expectation for a global net plant efficiency of around 50%. Consequently intermediate heat exchangers and recuperators being considered will require an effectiveness of 95% or higher.

Thus the heat exchangers will play a key role in projects such as the European Union "High Temperature Reactor Components and Systems," and "Rational and Objective for Integrated Project High Temperature Reactor Nuclear Technologies" and other non European Union Projects, which couple a helium cooled reactor to helium turbine plant.

Key issues will include:

- *Thermal design.*
- *Hydraulic design*
- *Mechanical design*
- *Containment and safety considerations*
- *Layout and compactness*
- *Cost*

In particular we will examine the development of the Printed Circuit Heat Exchanger (PCHE) to address these issues. Traditionally the PCHE is a high efficiency, high integrity compact plate type exchanger used primarily for gas applications on offshore facilities. From this a purpose designed recuperator and intermediate heat exchanger configuration have been developed, suitable for high temperature gas cooled reactor applications.

We conclude that the PCHE permits the key issues to be successfully addressed. The latest PCHE designs permit a simple, compact, high integrity, low cost arrangement. This high effectiveness exchanger is expected to be substantially cheaper than arrangements hitherto considered.

2 AIMS

The aim of this paper is to investigate the heat exchanger requirements for high temperature gas cooled reactors. Focus is given to the principle exchanger the gas / gas exchanger, although many of the considerations and conclusions are valid for the coolers and secondary exchangers.

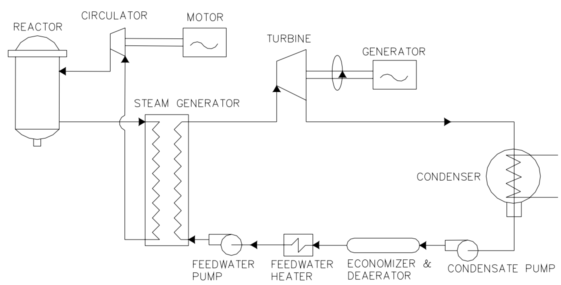
Finally the paper aims to show that although there are several exchanger types and configurations that appear to meet the requirements for gas cooled reactors, in practice there is only one. The only exchanger that is able to meet the thermal, hydraulic, mechanical, compactness and economic requirements of current projects, is the Printed Circuit Heat Exchanger (PCHE). Further it is only the PCHE that has the potential to be developed to higher temperatures and pressures to meet future requirements.

It is not the aim of this paper to make comparison between GT-MHR and PBMR, or direct cycle and indirect cycle, although from the comments about the heat exchangers some conclusions may be drawn.

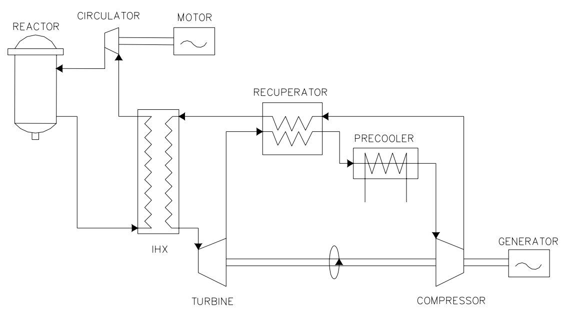
3 INTRODUCTION

If nuclear energy is to provide a viable cost-effective alternate to fossil fuels then global net plant efficiencies in the order of 50% must be achieved. Additionally safety requirements must be enhanced, and the associated cost of that safety must be reduced.

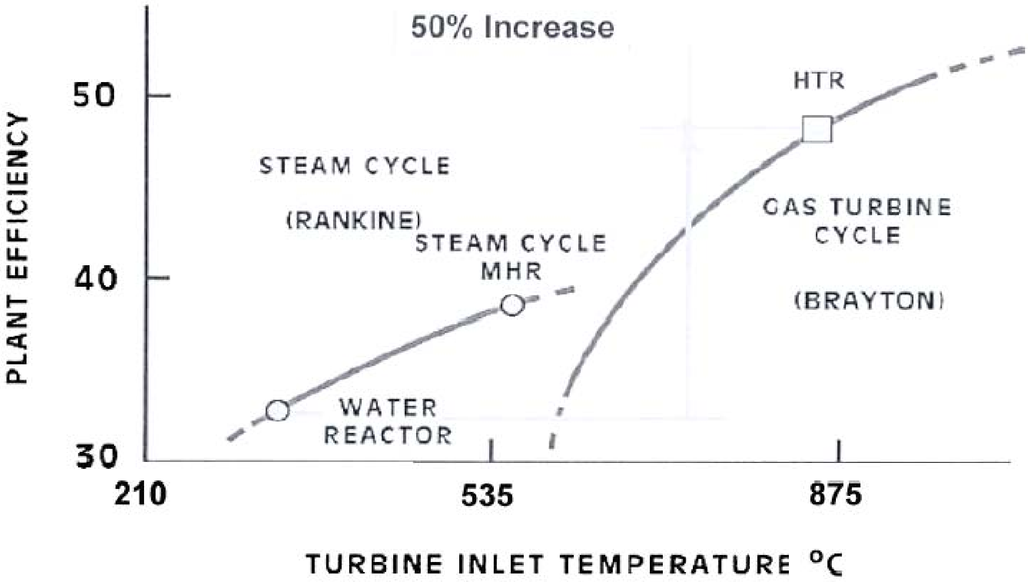
At present Light Water Reactors (LWR) using the steam or Rankine cycle achieve an efficiency of around 33%. However, the efforts required to assure safe operation are considerable.



The medium temperature indirect gas turbine cycle (MHTGR) offers some increase in efficiency up to 38%. The major weak point is the steam generator. The low heat transfer coefficients of helium when compared with water leads to the need for large steam generation units.

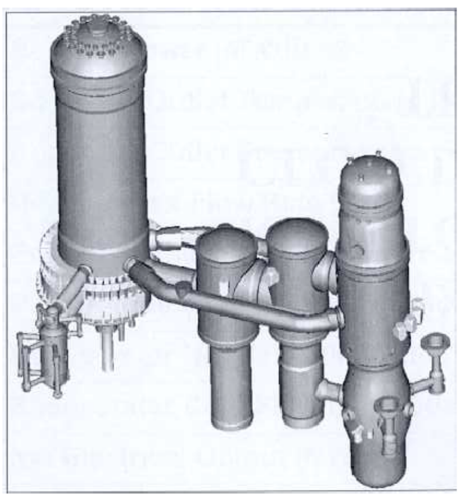


High temperature gas reactors have the unique ability to use the Brayton cycle. With the single phase Brayton cycle efficiencies of 48% can be easily achieved.

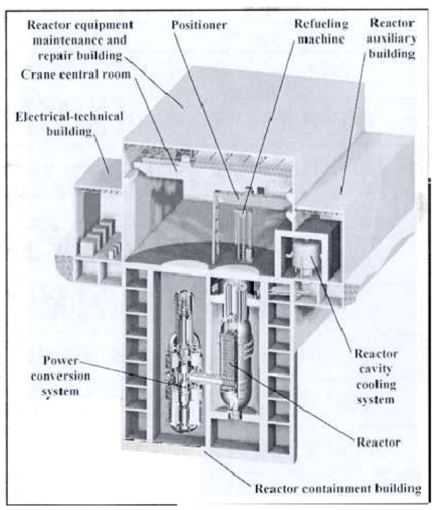


There are variants on the gas cooled reactor, for instance both GT-MHR and PBMR use the direct gas turbine cycle. The current GT-MHR concept has a reactor using conventional fuel and all of the rotating equipment associated with the power conversion system is on a single shaft. PBMR has a less conventional pebble bed reactor and the rotating equipment is split between three separate shafts.

PBMR



GT-MHR



However, except for differences in the size and overall duty, the requirements for the recuperator are very similar.

Another variant is the high temperature gas reactor with an indirect cycle.

The reactor is again cooled with helium, which is now on a separate primary loop. The secondary loop is also a gas loop; usually helium, although other fluids under consideration include air and nitrogen. For power generation, efficiencies in the order of 50% can again be achieved.

For this indirect cycle the recuperator is replaced by an intermediate heat exchanger and the operating conditions are somewhat different. Some perceive the separating of the primary and secondary side to be safer. However, it is easy to see that with this separation of primary and secondary sides it is possible to replace the power generation system with a hydrogen production facility, or any other facility where large quantities of heat are required.

Whether GT-MHR or PBMR, direct cycle or indirect cycle all of the high temperature gas cooled reactors have one thing in common. If a global net plant efficiency of around 50% is to be achieved there is a need for high efficient heat exchange. This paper looks at those heat exchange requirements, giving consideration to the following aspects:

- Thermal
- Hydraulic
- Mechanical
- Containment and Safety Considerations
- Space considerations
- Fouling
- Reliability
- Availability
- Economics
- Future developments and needs.

4 TYPICAL SPECIFICATIONS

Before starting to define the requirements of a suitable heat exchanger it is necessary to better understand some of the operating parameters. The table below summarises the recuperator specifications for two direct cycle exchangers, the PBMR and the GT-MHR Projects. In addition two typical specifications for indirect cycles are given.

Parameter	Units	Symbol	PBMR	GT-MHR	Indirect 1	Indirect 2
Thermal Duty	MW	Q	360	635	600	200
Hot Side Fluid	-		Helium	Helium	Helium	Helium
Hot Side Flow Rate	kg/s	M_H	198.0	316.0	277.2	63.2
Hot Side Inlet Temperature	°C	T_1	494.0	510.0	787.8	950
Hot Side Outlet Temperature	°C	T_2	143.8	125.0	371.1	340
Hot Side Inlet Pressure	MPa	P_1	3.00	2.63	6.21	4.0
Cold Side Fluid	-		Helium	Helium	Air	Helium
Cold Side Flow Rate	kg/s	M_C	183.0	313.0	1061.7	63.2
Cold Side Inlet Temperature	°C	T_3	102.0	105.0	243.3	290
Cold Side Outlet Temperature	°C	T_4	481.4	490.0	760.0	900
Cold Side Inlet Pressure	MPa	P_2	9.00	7.07	2.07	3.0
LMTD	°C		24.3	20.0	65.5	50.0
Thermal Effectiveness[1]	%	E	97	95	95	92
Pressure Drop[2]	%	dP	1.0	1.6	4.0	2.9

Note:

1 Thermal effectiveness is defined as:

$$E = (T_4 - T_3) / (T_1 - T_3)$$

2 Pressure Drop is defined as:

$$dP = [(DP_1 / P_1) + (DP_2 / P_2)] * 100$$

where DP equals inlet pressure minus outlet pressure.

5 DESIGN CONSIDERATIONS

5.1 Size and Containment.

The thermal duty of all the exchangers specified above are relatively large. The smallest is 200MW. This implies a large exchanger, especially when consideration is given to the thermal effectiveness (typically 95%) and the relatively low pressure drops. All of the direct cycle projects require the recuperator to be fitted inside the containment vessel. For PBMR the recuperator is to be installed immediately underneath the power generation turbine. For GT-MHR the recuperator is to be installed around the single rotating equipment shaft. Space is at a premium so the direct cycle recuperator must be a compact design. Mechanical, economic and safety considerations dictate that the containment vessel should be as small as possible.

For the indirect cycle safety considerations will probably dictate that the intermediate heat exchanger is again inside the containment vessel. Reasons for this include:

- Contaminant in the form of carbon particulate, picked up by the primary side helium as it flows through the reactor.
- Mechanical considerations discussed in section 5.2.

Without too much in-depth analysis, the need for a small compact exchanger has been established. Clearly, conventional shell and tube technology will not be suitable for either the direct cycle recuperator or the indirect cycle intermediate heat exchanger. A conventional U tube 10 MW HTR helium intermediate heat exchanger was built in Germany in the 1980s.[1] Although satisfying the specified parameters including an operating temperature in excess of 900°C this 10MW exchanger weighed some 135 tonnes. Given current requirements for a 200 to 650MW exchanger, the weight alone demonstrates that shell and tube technology is not a viable option.

5.2 Material & Mechanical Considerations

a Direct Cycle

With the direct cycle it is possible to design the recuperator assuming a differential pressure design. For both PBMR and GT-MHR the containment vessel atmosphere is helium under the hot stream outlet conditions. Hence the recuperator needs to be designed with a cold side design pressure of:

$$(P_2 - P_1) * \text{safety margin}$$

Assuming the safety margin is about 10%, a cold side design pressure in the range 5.0MPa to 6.6MPa is anticipated. On the hot side the design pressure needs to be little more than the stream pressure drop.

Based on normal operation design temperatures on both the hot and cold sides will be in the range of 550°C. Consideration must also be given to non design conditions, such as total unexpected loss of load on the power generator. Brief temperature excursions perhaps as high as 800°C may occur, under these non-design conditions. Under these transient conditions as the temperature increases, so the differential pressure falls. The increasing temperature and consequent reduction in design stress is offset by the fall in pressure.

It therefore seems reasonable to assume that an austenitic stainless steel such as SS316 will satisfy the design criteria for the direct cycle recuperator. Pressure vessel design codes such as ASME VIII Division 1 already allow the use of austenitic stainless steels such as SS316 to 815°C (1500°F). Although the majority of nuclear codes have not qualified austenitic stainless steels beyond the temperature requirements of Light Water Reactors.

Material and mechanical considerations therefore restrict exchanger selection to those types that can be fabricated in austenitic stainless steel or equivalent and withstand pressures of up to 6.6 MPa. This almost certainly prohibits the use of those plate type exchangers where support is only provided at the edge of the plate.

There is a further consideration under transient conditions where temperatures of up to 800°C might be expected. This probably prohibits the use of brazed structures. The brazing process uses low temperature melting point alloys to joins the different exchanger components. What is the braze integrity at 800°C? There seems to be little information in the public domain. Brazed products have been developed for high temperature aerospace applications. However, there can be little doubt that the brazed joint will have strength and creep characteristics that are inferior to the parent material properties. A brazed product will require specific development.

Given that the recuperator is expected to have a 30 year life or longer, is brazing a suitable joining process? Would it not be prudent to use an all welded construction, or a diffusion bond? With a diffusion bond there is no braze or filler material. Further, as the bonded structure is all parent material, it is reasonable to expect, and can be demonstrated, that parent metal properties are achieved. Therefore if the parent metal is suitable for use, the diffusion bonded core is also suitable.

However, the questions about braze integrity go unanswered. Brazed plate exchangers in a variety of configurations are widely used in a vast number of applications. These applications are almost exclusively at low temperature, often cryogenic. There is little literature or operational experience to support their use at temperatures above 200°C.

Obviously there is considerable literature on the precautions and design considerations to achieve good weld integrity.

b Indirect Cycle

With the in-direct cycle intermediate exchanger, operating pressures are similar to or lower than those present in the direct cycle recuperator. The examples specified in section 4 have a maximum operating pressure of 6.2MPa, although others have considered operating pressures as high as 9.0MPa. As the two sides of the exchanger are independent loops the use of differential pressure design is less appropriate. Therefore design pressures of up to 10.0MPa can be expected.

Operating temperatures are also higher, with hot side inlet temperatures as high as 950°C being specified.

For this exchanger, material selection and mechanical design philosophy become significant factors. As stated in the previous section, few nuclear codes qualify materials much beyond the requirements of light water reactors. Conventional pressure vessel design codes such as ASME VIII Division 1 allow the use of Incoloy 800HT (UNS N08811) and Alloy HX (UNS N06002) to design temperatures as high as 898°C (1650°F). It can further be expected that alloys such as Inconel 617 (UNS N06617) could be used to design temperatures as high as 1000°C.

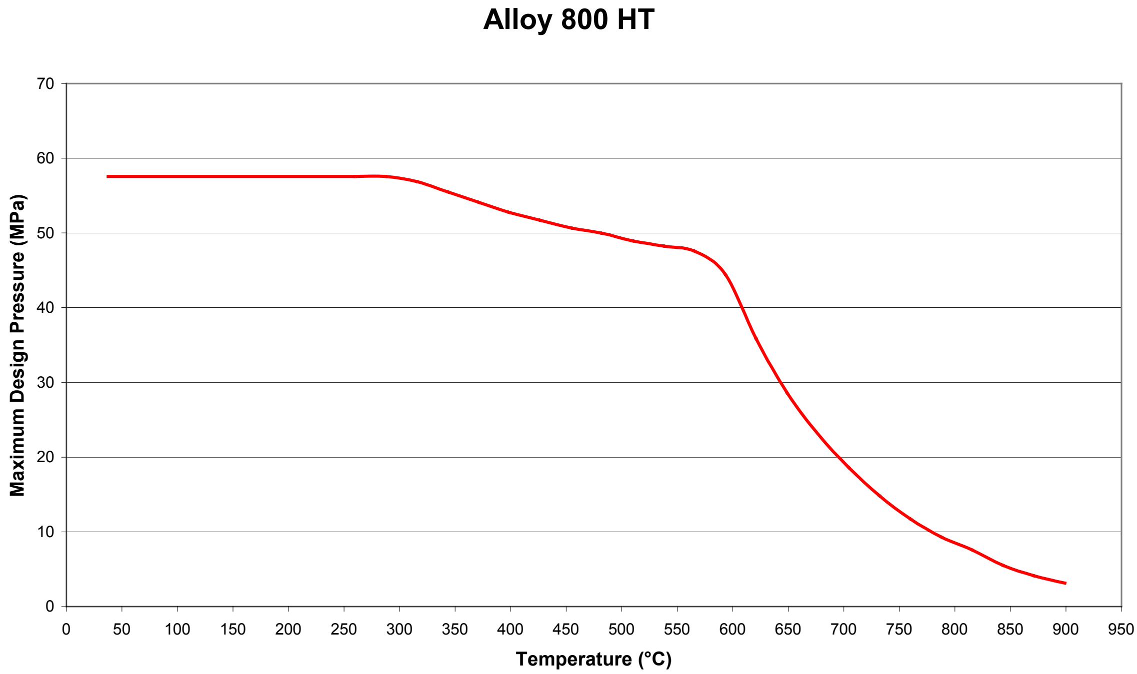
This does not provide the total solution; typical allowable design stresses at 900°C are as follows:

- Incoloy 800HT 6.27MPa²
  (based on a creep life of 10^5 hours)
- Alloy HX 8.27MPa²
  (based on a creep life of 10^5 hours)
- Inconel 617 17.45MPa
  (based on a creep life of 10^4 hours)

Assuming a design life of 30 years is required at 900°C normal alloys would not permit a design stress much beyond 6MPa. Applying normal design criteria this restricts design pressures to about 50% of this value. To exceed these temperature and strength limitations there will probably be a need to employ oxide dispersion strengthened alloys.

If intermediate heat exchangers are to be of normal metallic construction we can conclude the following, irrespective of exchanger type:

1 Design temperatures and pressures must be restricted such that the allowable design stress at temperature is at least twice the design pressure.



2 Consideration must also be given to differential pressure design, if the operating conditions are not to be limited to more moderate temperature and pressure combinations.

As the fluids are independent, precautions will be necessary to maintain the correct pressure differential in the event of unscheduled upset. Whereas an upset in the direct cycle gives rise to thermal transient considerations, an upset in the indirect cycle will also result in pressure transient considerations.

What becomes apparent is that given the material and allowable stress considerations, only an exchanger type where all joints have parent (or near parent) properties should be considered. Brazed structures would almost certainly not be fit for purpose if proper consideration is given to mechanical and design life considerations.

5.3 Thermal and Hydraulic Considerations

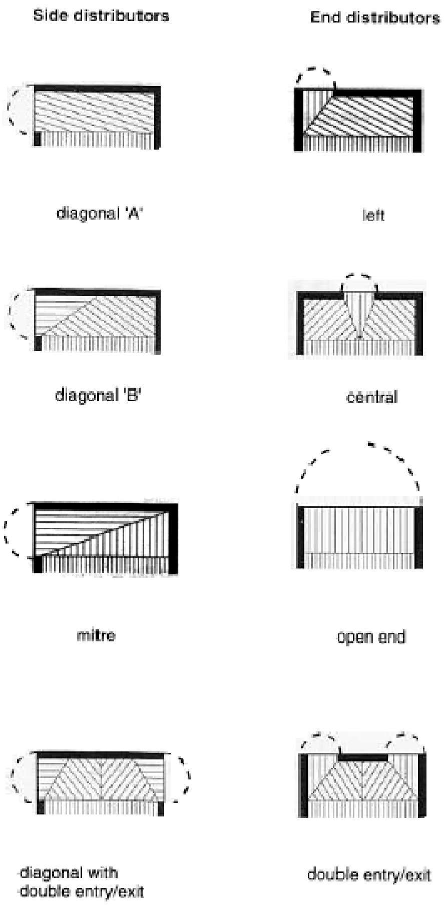
For both the direct and indirect cycles, the exchanger specifications require a thermal effectiveness of 95% or more; typically between 10 and 20 NTUs. Further, allowable pressure drops are low. This is particularly true for the direct cycle recuperator.

Hence, irrespective of exchanger type, the hot and cold fluid contact arrangement will need to be predominantly counter current. Further, the flow length will almost certainly be limited by pressure drop.

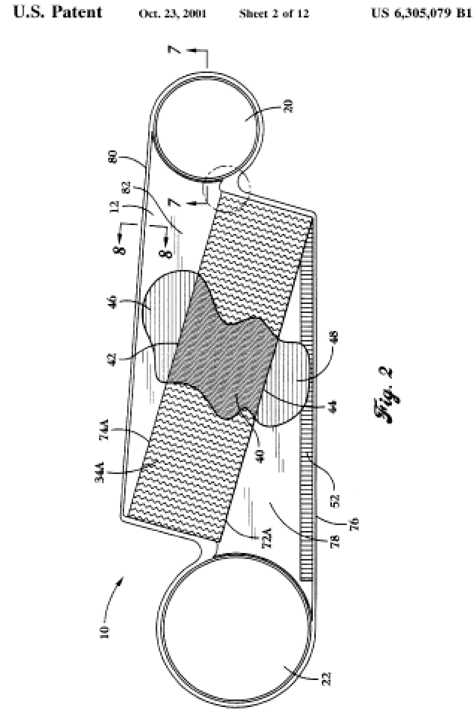
As discussed in section 5.1, non-compact heat exchangers for this type of duty will be excessively large 135 tonne per 10MW, implying a 8,000 tonne recuperator for a 600MW (thermal) reactor.

The majority of compact heat exchangers tend to be plate type, or plate variant. Therefore we can conclude that the heat exchanger will be a plate type exchanger with counter current contact arrangement. However, no plate type exchanger can be truly counter current, as the plate must have width as well as length and the fluid must be introduced across the full width of the plate. Therefore every plate exchanger must have some cross flow component.

Fluid introduction and the cross flow component can be handled in several ways. With conventional plate fin type exchangers a distributor is used on one or both of the streams. Examples are given in the table below.



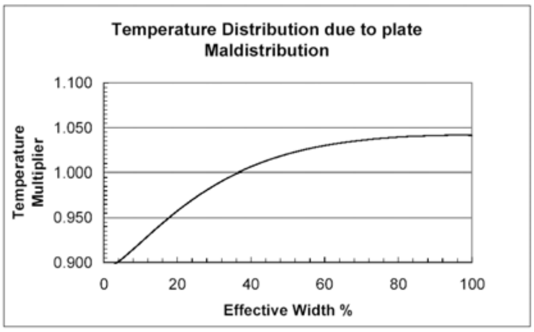
Typically with this type of exchanger the distributor is a relatively small proportion of the plate, 20% or less. The Ingersoll-Rand plate fin also uses a distribution system.



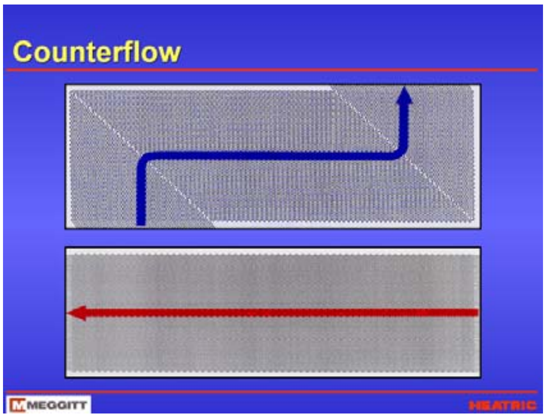
Less is known about the Ingersoll Rand plate fin exchanger. From drawings available in the public domain the distributor area is however large compared to the plate area and active flow length.

With a distributor it is usual for the fin density to be lower than in the heat transfer area; typically the hydraulic mean diameter in the distributor is 2.5 to 3.0 times greater than in the heat transfer area. As a consequence, heat transfer and pressure drop characteristics in the distribution system are low compared with the heat transfer area. However, a flow path going across the plate prior to a change in temperature will have different pressure drop characteristics to a fluid changing temperature and then crossing the plate.

This results in flow maldistribution, the smaller the aspect ratio the greater the maldistribution effect. As the figure below indicates, due to the high effectiveness, flow maldistribution causes significant under performance of some passages but there is very limited opportunity for other passages to over perform. The result is an operational effectiveness below that calculated or modelled. Exchangers such as the Ingersoll Rand plate fin, where the effective width seems to be large in comparison to the flow length may prove to be very susceptible to this maldistribution mechanism.



The normal geometry diffusion bonded PCHE, offers an alternative to distributors.



The active passage geometry is used in the cross flow region and there is no distributor. Effectively the exchanger has a counter current contact arrangement with cross flow entry and exit regions. All of the plate is active, but the efficiency of the cross flow regions is small, for high effectiveness duties. Further, there is flow maldistribution similar to that found with the plate fin and their distributors. Increasing the plate aspect ratio and changing the passage geometry in different parts of the plate can reduce but not eliminate this phenomenon.

One significant advantage of having no distributors is reduced header maldistribution. As PCHE headers are often longer than with other exchanger types, it is often wrongly assumed that header maldistribution is greater. In fact plate type exchangers with distributors have significantly greater header maldistribution, even though they have shorter headers.

If correctly analysed, the following can be concluded about header pressure variations and potential maldistribution mechanisms:

- There will be a pressure profile along the header due to the dynamic head effect (the difference between total and static pressure). Near the nozzle the dynamic head is large; remote from the nozzle the dynamic head tends to zero. This effect is independent of length. For any given header diameter, the difference in inlet (static) pressure between the first and last plate is the same irrespective of the number of plates between.

- Any gravitational effect is negligible.

- Frictional losses are present, but, they are also negligible; at least an order of magnitude smaller than the dynamic head effect.

The only significant component is the dynamic head within the header. For those exchangers that have no distributors, such as PCHEs, the header diameter is at least equivalent to the exchanger effective width. For those exchangers with distributors, such as plate fins, the header diameter is just sufficient to cover the distributor, whose width is a fraction of the effective width. The dynamic head is proportional to the square of the header diameter. Therefore, assuming a distributor whose effective opening is 50% of the plate effective width, a plate fin header dynamic head would be 4 times greater than that found in the equivalent PCHE. The potential maldistribution mechanism will equally be 4 times larger.

To conclude, the normal geometry PCHE has some advantage over plate fins in that header maldistribution is significantly smaller in a PCHE. The traditional PCHE and the plate fin are both subject to plate maldistribution. Further, whether because of distributors or cross flow region both have significant areas (20% of the plate or more) where heat transfer is not very effective. For these reasons and others, Heatric decided to develop a new contact arrangement and exchanger configuration for their product the PCHE.

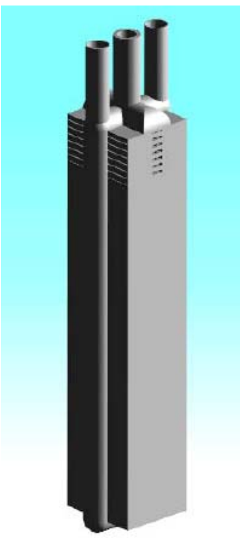
At this point it is not possible to disclose the exact internal geometry of the "New Concept PCHE." However, the new design exhibits the following thermal and hydraulic features:

- All active heat transfer passages are in pure counter current configuration.

- The fluids are distributed to the active passages via internal ports. Further, the plate active length to width ratio is greater than 7:1. As a consequence there is no significant plate maldistribution.

- The herringbone (zig-zag) passage geometry has been reconfigured to enhance turbulence, and therefore heat transfer coefficients. This gives a 60% increase in overall U.

- The reconfigured plate and passage geometry offers reduced pressure drop characteristics (Up to 55% reduction in overall pressure drop).



5.4 Fouling Considerations

All compact exchangers are to some extent susceptible to fouling. This is inevitable, as they are compact with reduced passage size and increased passage tortuosity to enhance heat transfer coefficients and thus reduce the exchanger size.

For this application the service will be essentially clean, particularly when compared with many of the hydrocarbon applications where both plate fins and PCHEs are widely employed. The only fouling agent will be carbon particulate from the reactor. This particulate will be less than 1 micron in size and the anticipated particulate load will be in the order of 0.1kg /MW at the end of the reactor life.

With a minimum exchanger operating temperature in the order of 100°C no moisture will be present to act as a binding agent. Particle agglomeration is therefore improbable. Therefore the only question is whether the particles pass through the exchanger.

In the case of the PCHE the answer is yes. The fluid passages are approximately semicircular with a radius of 0.6mm. It is therefore reasonable to assume that a particle smaller than one third of the passage radius will pass through the exchanger. Hence we can determine that particulate with a maximum dimension less than 0.2mm (200 micron) will pass through the exchanger. A particle some 2 orders of magnitude greater than the actual graphite particles would pass through the exchanger.

PCHE passages are also continuous. Any passage can be followed from inlet to outlet; there are no breaks or discontinuities. Hence, there are no dead areas or areas of low velocity and there is high wall shear throughout the exchanger internals. There is no possibility of particles settling or of adhesion to the wall.

With exchangers of plate fin variety the minimum dimension is not the fin height but the distance between fins. A high performance fin would have a fin density of about 850 fins per meter. The foil thickness would be of the order of about 0.2mm, hence the clearance between fins is about 1mm. However for serrated fins, the next fin interrupts this clear way. It is therefore necessary to divide this distance by two and deduct a further foil thickness. The actual clearance is therefore about 0.4mm. Again assuming a particle smaller than one third of the passage minimum dimension will pass through the exchanger we find that particles smaller than 0.13mm (130micron) will pass through the exchanger. This clearance is smaller than for the PCHE, but still some 2 orders of magnitude greater than the actual graphite particles.

To avoid particulate fouling within the exchanger, emphasis needs to be put on continuous passages. Exchangers with multiple fin pads and or serrated fins have a greater potential fouling[5]; consequently they are probably not suited to this application.

5.5 Containment and Safety Considerations

No heat exchanger is designed to leak. Consideration should however be given to the consequence of a leak. For either the direct or the in-direct cycle, it is probable that the exchanger, irrespective of type will be installed inside the containment vessel. As this vessel will almost certainly have an atmosphere of either the hot side outlet or the cold side inlet, both internal leaks* and external leaks* will have the same effect; they will represent a bypass and fall in efficiency. Therefore it is only important to give consideration to the likely leak magnitude.

The PCHE has one feature that makes it unique among compact exchangers, its continuous passages. Each passage on each plate can be regarded as a separate pressure vessel. Therefore a leak within a PCHE can be regarded as a leak from a semicircular passage of radius 0.6mm.

For a shell and tube exchanger if the same criterion is applied, one must consider the leak of a ruptured tube. Assuming standard 15mmNB tube, at choke velocity this leak will be about two orders of magnitude greater than the equivalent PCHE leak.

If a normal brazed plate type exchanger is considered, the passages are non-continuous, due to different fin pads and serrated fin, so consideration must be given to a leak from a whole plate. Dependent upon plate size and fin height this would again be a leak at least two orders of magnitude greater than the equivalent leak in a PCHE.

The PCHE core having no brazed joints is less likely to leak than more conventional exchanger types, which are dependent upon joints of less than parent metal properties.

* *An internal leak is regarded as a leak between side A to Side B. An external leak is regarded as a leak from one side of the exchanger to the atmosphere of the containment vessel.*

5.6 Cost and Economics

It is difficult to obtain realistic prices for many of these exchangers, but estimated weights are available. For any given service and operating parameters, it is also likely that materials of construction will be similar. Conclusions as to price can therefore be drawn from the following table.

Exchanger Type	Weight / Duty (tonnes / MW)
Shell & Tube[1]	13.5
Brazed Plate Fin[6]	0.2
PCHE	0.2

Assuming weight is an accurate indicator of cost, the above shows shell and tube to be more than an order of magnitude more expensive. This ignores the additional cost associated with larger containment vessels, supports etc.

Based just on weight there is little to chose between PCHE and brazed plate fin. There is a need to look at associated costs, pipework costs etc. For instance a 360MW PBMR recuperator could be supplied as approximately 48 brazed Exchangers or 6 PCHEs, yet both are designed to the same specification, to fit in the same containment vessel. Pipework, manifolds, supports and assembly for a configuration of 6 exchangers will be considerably less than with 48.

One can also conclude that an all diffusion bonded and welded structure such as the PCHE, where parent metal properties are achieved in every joint will have a longer design life than an exchanger containing weaker brazed joints.

6 CONCLUSIONS

1 There are many and varied reasons why the heat exchangers for high temperature gas cooled reactors need to be compact. Compact exchangers offer a smaller, safer cheaper exchanger, with equal or superior thermal and hydraulic performance.

2 Of all of the compact exchangers the Printed Circuit Heat Exchanger (PCHE) is superior in nearly every aspect.

- The PCHE is the only compact exchanger that offers parent metal strength and properties throughout the entire exchanger. It is not dependent on brazed joints.

- Developments of the herringbone or zig-zag fluid passage, gives heat transfer coefficients that are equal to or greater than all other surfaces, including serrated fin.

- The same fluid passage gives substantially lower pressure drop characteristics than can be associated with high performance fins.

- Heatric's new contact arrangement offers a plate with pure counter current flow. Unlike other arrangements with or without distributors this flow arrangement is virtually free from maldistribution mechanisms.

- As the PCHE has no conventional distributors header losses and malistribution mechanisms are smaller than for other compact exchanger types.

- The PCHE's continuous passage geometry results in an exchanger that is less susceptible to fouling than other compact types. The PCHE has larger passage clearance and is free from dead areas.

- The PCHE's continuous passages results in the consequence of a leak being two orders of magnitude less than other exchanger types, compact or non compact.

- The weight of a PCHE is less than or equivalent to other compact exchangers. However, the number of sections is considerably less. This will result in competitive purchase prices, together with reduced containment, pipework, manifold, support and assembly costs.

- The all diffusion bonded and welded structure will also have a longer life, than a brazed structure.

3 In the case of the direct cycle recuperator the PCHE is fully developed and manufacture could begin immediately. For the indirect cycle intermediate heat exchanger, dependent upon design temperature and pressure, some development work is required. However this work is on material development and design philosophy not the exchanger.

7 REFERENCES

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