XA0103035

COMPACT HEAT EXCHANGER TECHNOLOGIES FOR THE HTRs RECUPERATOR APPLICATION

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Abstract:

Modern HTR nuclear power plants which are now under development (projects GT-MHR, PBMR) are based on the direct cycle concept. This concept leads to a more important efficiency compared to the steam cycle but requires the use of high performance components such as an helium/helium heat exchanger called recuperator to guarantee the cycle efficiency. Using this concept, a net plant efficiency of around 50% can be achieved in the case of an electricity generating plant. As geometric constraints are particularly important for such a gas reactor to limit the size of the primary vessels, compact heat exchangers operating at high pressure and high temperature are attractive potential solutions for the recuperator application. In this frame, Framatome and CEA have reviewed the various technologies of compact heat exchangers used in industry. The first part of the paper will give a short description of the heat exchangers technologies and their ranges of application. In a second part, a selection of potential compact heat exchangers technologies are proposed for the recuperator application. This selection will be based upon their capabilities to cope with the operating conditions parameters (pressure, temperature, flow rate) and with other parameters such as fouling, corrosion, compactness, weight, maintenance and reliability.

1 INTRODUCTION

1.1 Modern HTRs features

The modern HTRs which are now under development (projects GT-MHR, PB-MR) are based on the direct cycle concept. In this case the primary coolant circuit of the nuclear core and the driver circuit of the electric generator is the same circuit. The simple cycle of the helium is called Brayton cycle (figure 1). The hot helium from the core outlet flows directly through the turbine where it is expanded. Then it is cooled before to be compressed and goes back to the core. The turbine drives the electric generator. The high efficiency of the cycle can be still further improved (up to 50%) using a helium/helium heat exchanger called recuperator between the low and high pressures sides. In this case, the remaining gas energy at the turbine outlet is recuperated by this exchanger and is used to preheat the helium at the core inlet. It must be noted that the recuperator can be located inside the pressure vessel and, therefore, is not a containment barrier of the primary coolant.

The recuperator needs to have a high efficiency (95%), but also requires high mechanical characteristics as it operates at high pressure and high temperature. Furthermore, it should be as small as possible to limit the size of the vessel. These constraints lead to evaluate compact heat exchanger technology for modern HTRs recuperator application.

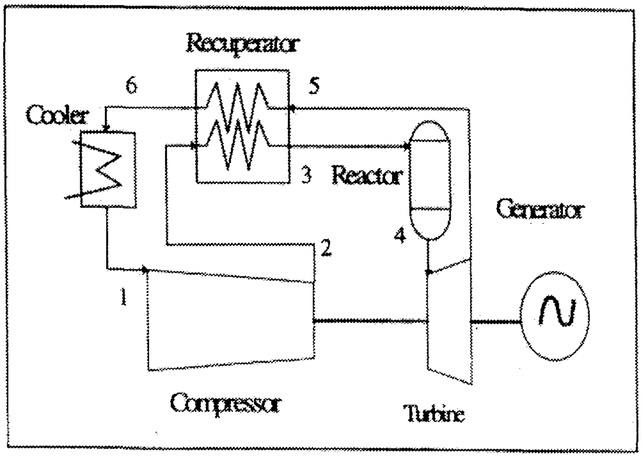


Figure 1. Brayton cycle with recuperator.

1.2 Recuperator operating conditions

For a large power reactor (GT-MHR type) the steady state operating conditions are summarised in the table 1.

TABLE 1. RECUPERATOR TECHNICAL CHARACTERISTICS

Parameter	Unit	Hot side (LP side)	Cold side (HP side)
Thermal capacity	MW	630	630
Inlet temperature	°C	507	107
Outlet temperature	°C	127	487
Inlet pressure	MPa	2.6	7.2
Flow rate	kg/s	320	320

The pressure losses along the HP and LP sides should be as low as possible (<1% of the nominal pressure).

During abnormal events, the recuperator inlet temperature can rise up to 650 °C.

The life time is expected to be the same as the nuclear plant (e.g. 60 years).

The helium contents (H_2O, CO, CO_2, H_2,...) and also solid graphite particles can induce respectively a risk of corrosion and a risk of fouling of the recuperator elementary channels.

1.3 Geometric constraints

The recuperator is located inside the pressure vessel at the turbine outlet. A modular concept is generally proposed to facilitate the maintenance operations (dismantled modules) or repair operations (plugging of leaky modules). These modules can be arranged in an annular space around the turbo-machine rotor.

To limit the size of the primary vessels, compact heat exchangers operating at high pressure and high temperature are attractive potential solutions for the recuperator application.

2 COMPACT HEAT EXCHANGER TECHNOLOGY

2.1 Classification of compact heat exchangers

Heat exchangers could be classified in many different ways such as according to transfer processes, number of fluids, surface compactness, flow arrangements, heat transfer mechanisms, type of fluids (gas–gas, gas–liquid, liquid–liquid, gas–two-phase, liquid–two-phase, etc.) and industry. Heat exchangers can also be classified according to the construction type and process function. Refer to Shah and Mueller [1988] for further details. In the following chapters only non-tubular heat exchangers will be described.

2.2 Plate Heat Exchangers

Plate heat exchangers (PHE's) were formerly used for milk pasteurisation and gradually became the standard choice for heat treatments in the liquid food industry. The facility of dismantling plate heat exchangers is one of the main reasons for their large use in the food industry. Furthermore, as the heat transfer coefficients are high, the fluid path length will be shorter and relatively well defined. Due to the lack of large dead areas in the channels, the corresponding residence time distribution is short and very homogeneous.

Afterwards, with the developments of larger plates, their use began to grow quickly in the chemical, petrochemical, districts heating and power industries, but essentially for single phase duties. The concept of phase change in PHE's started up in the 70's for OTEC applications (Ocean Thermal Energy Conversion) and the working fluids were Freon R22 or ammonia (Panchal and Rabas [1993]). These first studies on evaporation and condensation have been used for the development of PHE's in the refrigeration industry (Kumar [1992], Syed [1992], Navaro and Bailly [1992], Sterner and Sunden [1997], Pelletier and Palm [1997] and Palm and Thonon [1999]). Now PHE's become more often used in the process industry (Patel and Thomson [1992] and Brotherton [1994]), but their use is still not widespread.

In terms of technology, PHE's are made of pack of corrugated plates which are pressed together. The plate size ranges from 0.02 m^2 to over 3 m^2 with conventional pressing technology (figure 2), but can reach up to 15 m^2 for explosion formed plates (figure 3). The hydraulic diameter lies between 2 and 10 mm for most common plates, but free passages and wide gap plates exist for viscous fluid applications. Typically, the number of plates is between 10 and 100, which gives 5 to 50 channels per fluid. Furthermore, the use of high quality metal and the manufacturing techniques lead plate heat exchangers to be less prone to corrosion failure than shell and tube units (Turisini et al [1997]).

To insure the tightness three technologies are available: gaskets, welding and brazing. Gasketed PHE is the most common type, and the gasket material is selected in function of the application (temperature, fluid nature ...). Temperature up to 200°C and pressure up to 25 bars can be achieved by such heat exchangers. For applications where gaskets are undesirable (high pressure and temperature or very corrosive fluids), semi-welded or totally welded heat exchangers are available (figure 4). The last variant is the brazed plate heat exchanger. The plate pattern is similar to conventional gasketed units, but tightness is obtained by brazing the pack of plates. For common applications copper brazing is used, but for ammonia units nickel brazing is possible. This technology leads to inexpensive units, but the plate size is generally limited to less than 0.1 m^2. The counterpart is that the heat exchanger cannot be opened, and fouling will limit the range of application.

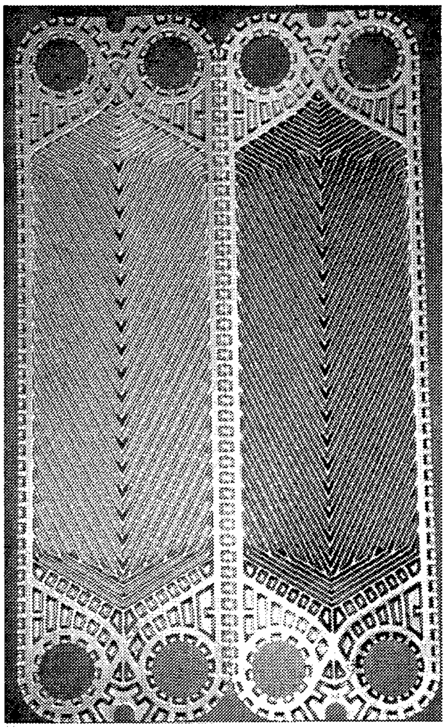


Figure 2. View of corrugated plates(courtesy of Alfa-Laval Vicarb).

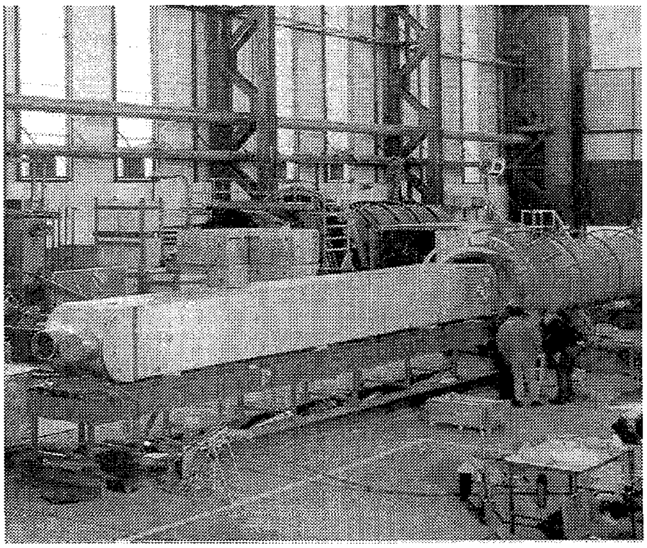
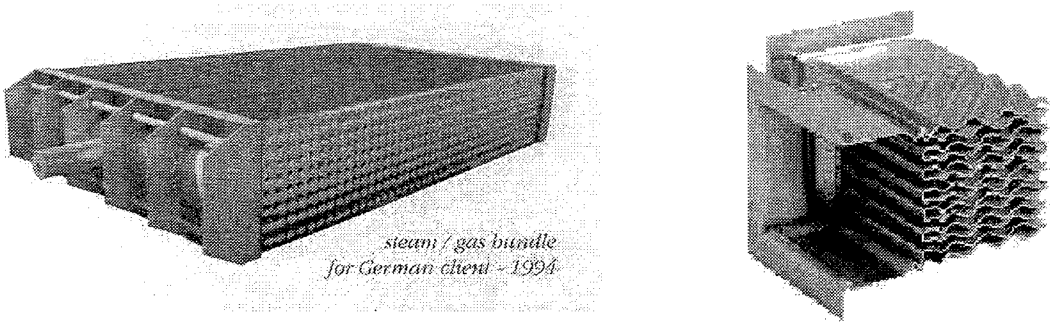


Figure 3. Explosion formed plate(courtesy of Packinox).



(courtesy of Ziepack) (courtesy of Alfa-Laval Vicarb)

Figure 4. View of welded plate heat exchangers

2.3 Spiral Heat Exchanger

The spiral heat exchanger (SHE) consists of two metal sheets that are welded together then rolled to obtain spiral passages. The passages can be either smooth or corrugated, in some cases studs or spacers are introduced between the metal sheets. These devices have two functions, first to adjust the spacing and secondly to induce turbulence that increases heat transfer. The general flow configuration can be crossflow (single or multipass) or counterflow depending on the configuration of the inlet and outlet distribution boxes. The heat transfer surface ranges from 0.05 m^2 for refrigeration applications up to 500 m^2 for industrial processes. Spiral heat exchangers are often used for phase change application as the geometry of the hot and cold stream channels can be adapted to the process specifications.

Recent developments in manufacturing technologies (laser welding) allowed to manufacture cost effective recuperators based on a spiral concept (figures 5 and 6) or folded plate recuperator (Oswald et al [1990], Mc Donald [1990] and [2000]).

2.4 Plate and shell heat exchangers

The basic principle of these heat exchangers is to insert a bundle of plate in a shell. On the plate side, the fluids flow inside corrugated or embossed channels (more often in two passes). On the shell side, the flow is similar to shell and tube heat exchangers, and baffles can be inserted. This technology can be used for revamping application as the shell can be kept identical to that of the replaced bundle of tubes.

These heat exchangers are often used in the process industry as boilers (boiling on the shell side) as high pressures can be reached very easily on the shell-side. Furthermore, adopting large gap on the shell side allows using dirty services, as cleaning is possible by removing the bundle of plates.

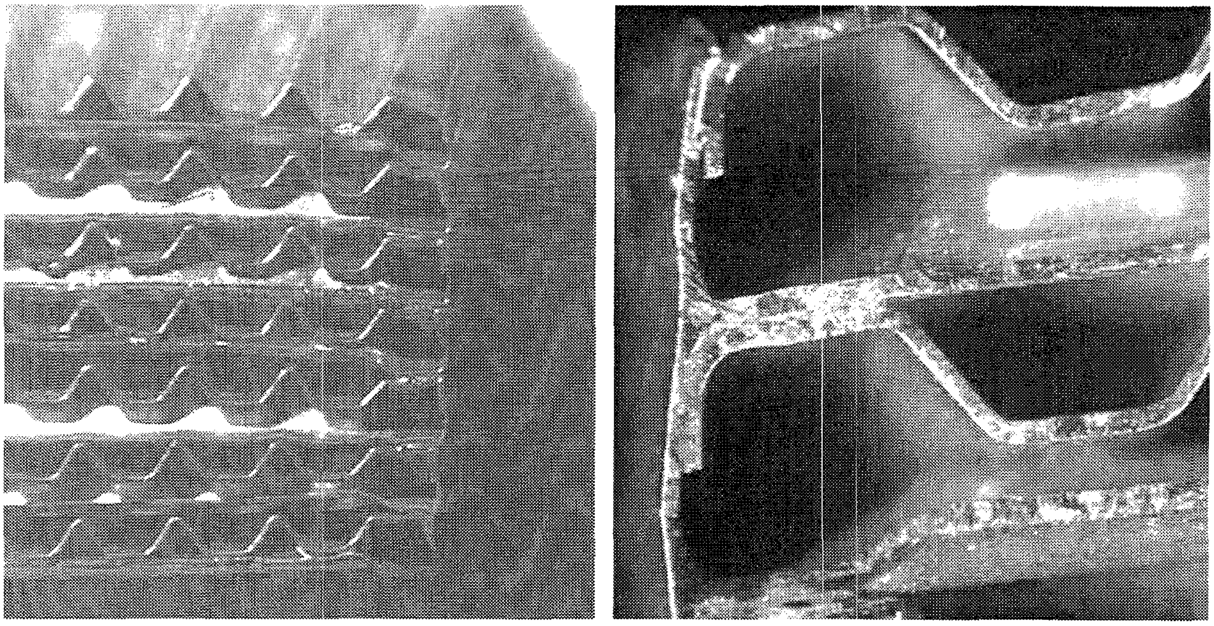


Figure 5. Laser welding of a spiral recuperator (courtesy of ACTE).

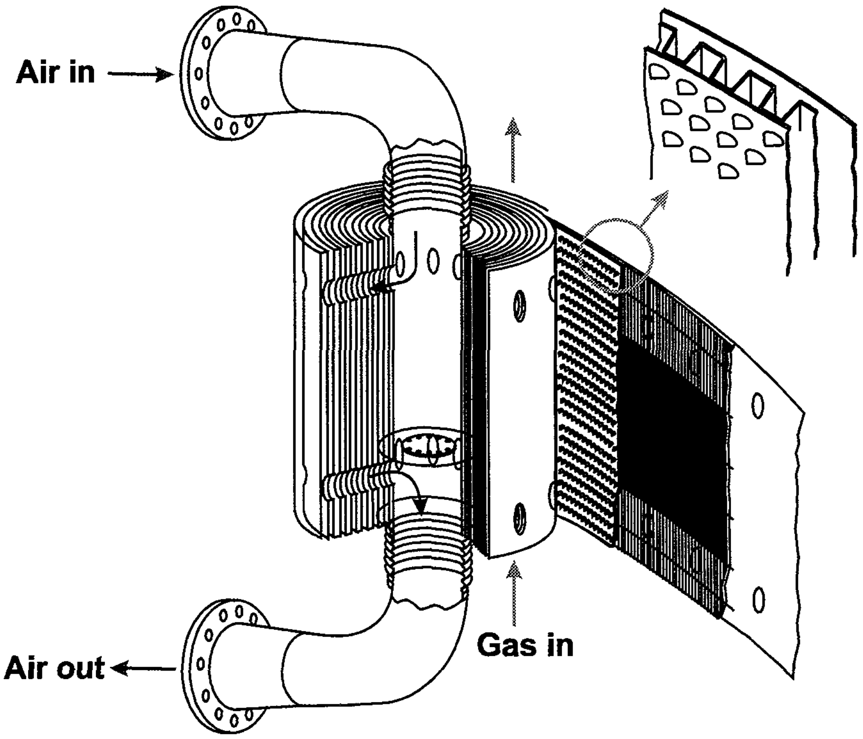


Figure 6. Spiral heat exchanger for gas turbine systems (courtesy of Rolls-Royce).

2.5 Plate-Fin Heat Exchangers

Aluminium plate-fin heat exchangers (PFHE) were initially developed in the 40's to provide compact, light and high efficient heat exchangers for gas/gas applications in the aerospace industry. As the mechanical characteristics of aluminium are increased at low temperatures, this technology has been used since 1950 for liquefaction of natural gases. Nowadays, aluminium plate-fin heat exchangers are extensively used in applications such as air separation, hydrocarbon separation, industrial and natural gas liquefaction (ALPEMA [1994] and Lundsford [1996]). Plate fin heat exchangers offer process integration possibilities (12 simultaneous different streams and more in one single heat exchanger) and high efficiency under close temperature difference (1 to 2 °C) in large variety of geometric configurations.
The brazed plate-fin exchanger consists of stacked corrugated sheets (fins) separated by flat plates, forming passages which are closed by bars, with openings for the inlet and outlet of fluids.

In its simplest form, a heat exchanger may consist of two passages, with the cooling fluid in one passage and the warming fluid in the other. The flow direction of each of the fluids relative to one another may be counter-current, co-current or cross-flow.

The fins and the parting sheets are assembled by fusion of a brazing alloy cladded to the surface of the parting sheets. The brazing operation is made in a vacuum furnace in which the brazing alloy is heated to its point of fusion. All parts in contact are bonded by capillarity action. Once the brazing alloy has solidified, the assembly become one single block. All passages for flow distribution and heat transfer of the streams are contained in the internal geometry of the block. Inlet and outlet headers with nozzles for the streams are fitted, by welding, around the openings of the brazed passages. These nozzles are used for connecting the heat exchanger to existing plant pipe-work.

Numerous fin corrugations have been developed, each with its own special characteristics (figure 7). Straight and straight perforated fins act like parallel tubes with a rectangular cross-section. Convective heat exchange occurs due to the friction of the fluid in contact with the surface of the fin. The channels of serrated fins are discontinuous and the walls of the fins are offset. For air flows, louver fins are extensively used, while for process applications (single and two-phase) continuous or offset strip fins are used.

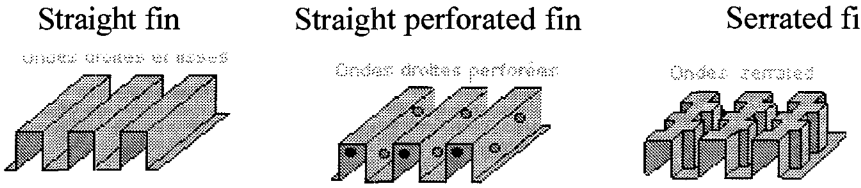

Straight fin Straight perforated fin Serrated fin

Figure 7. Different fin geometry.

For higher temperature applications or when aluminium is not acceptable, stainless steel (temperature up to 700°C) or copper materials can be used. For very high temperature (gas turbine heat recovery ; $T > 1200°C$), a ceramic plate fin heat exchanger has also been developed (Ferrato and Thonon [1997]).

For high pressure application in the hydrocarbon and chemical processing industries, a titanium compact heat exchanger has been developed by Rolls-Laval (figures 8 and 9). This heat exchanger consists of diffusion bonded channels that are created by super-plastic forming of titanium plates (Adderley and Fowler [1992]). This heat exchanger can handle high pressure and corrosive fluids and is suitable for marine applications.

2.6 Microchannels Heat Exchangers

Microchannels heat exchangers refer to compact heat exchangers where the channel size is around or lower than 1 mm (Mehendale et al [1999]). Such heat exchangers have been developed for severe environment such as offshore platforms (Johnston [1997]). New applications are also arising for nuclear high temperature reactors (Takeda et al [1997]). To manufacture such small channels several technologies are available (Tonkovitch [1996]). chemical etching, micromachining, electron discharge machining ...

The processing technique is as flexible as for plate-fin heat exchangers, and crossflow and counterflow configurations are employed. The main limitation of microchannel heat exchanger is the pressure drop, which is roughly inversely proportional to the channel diameter. For high pressure applications, the pressure drop is not a constraint, but for other fields of application it will be the main barrier to the use of such heat exchangers.

The most common one is the printed circuit heat exchanger developed by the Heatric Company. The channels are manufactured by chemically etching into a flat plate. The plates are stacked together and diffusion bonded, these heat exchangers can support pressure up to 500-1000 bar and temperature up to 900°C. The typical size of the channels is 1.0 by 2.0 mm (figures 10 and 11), and the plate size can be up to 1.2 × 0.6 m.

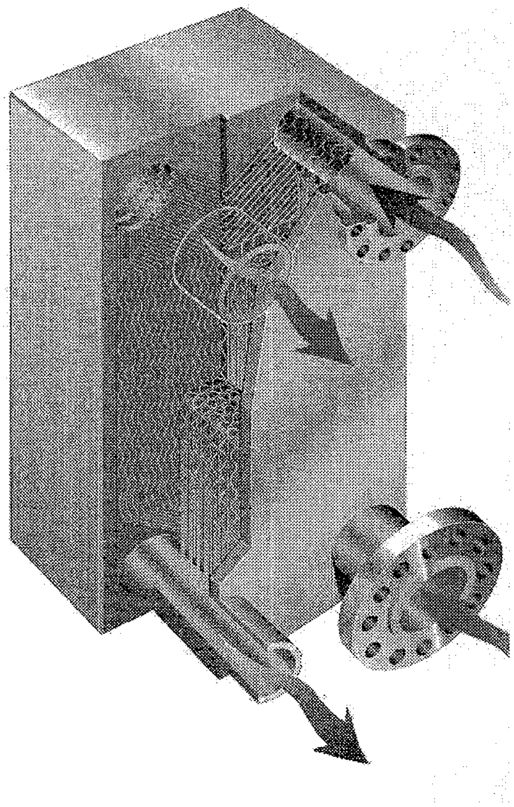


Figure 8. Schematic view of the heat exchanger (Rolls-Laval).

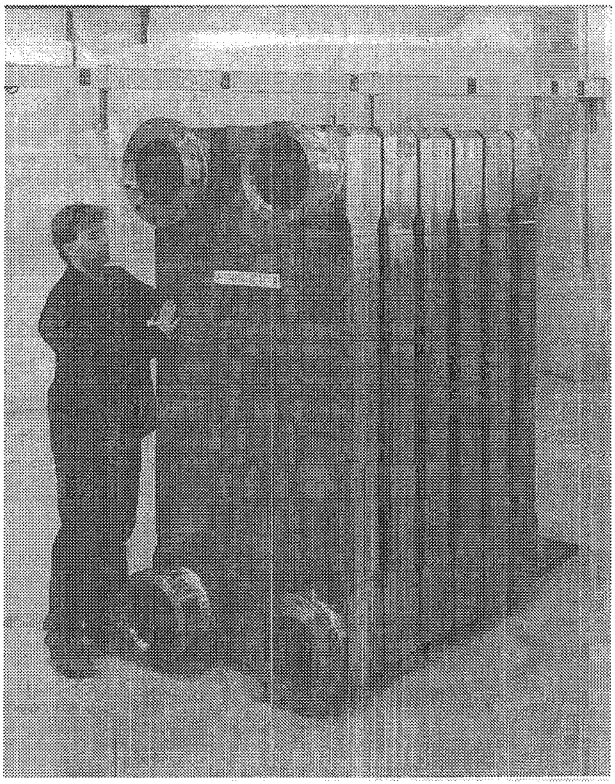


Figure 9. Picture of a titanium compact heat exchanger (Rolls-Laval).

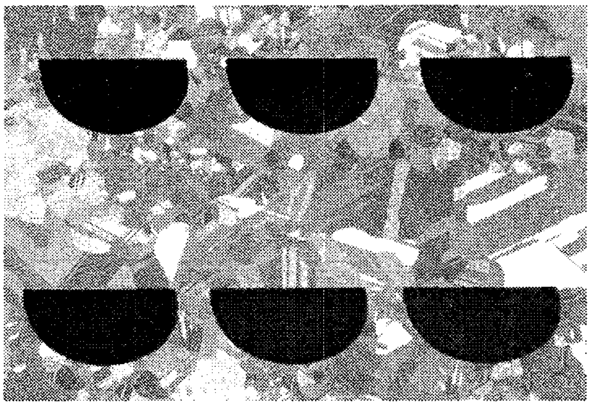


Figure 10. Detail of the bonded plates.

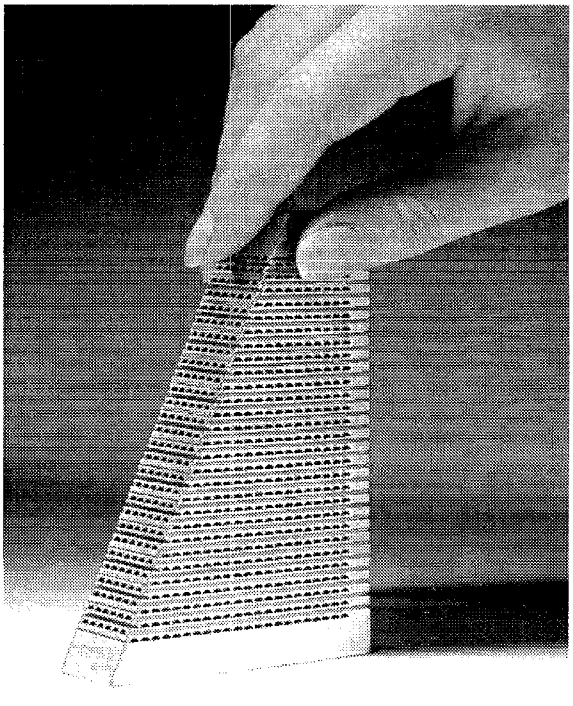


Figure 11. Printed circuit heat exchanger (courtesy of Heatric).

After diffusion bonding, the blocks are welded endplate to endplate to suit duty, then the headers are welded to the blocks to cover inlet and outlet. Headers are in rolled plate, cast or HIP (Hot Isostatic Pressing).

Diffusion bonded heat exchangers are often used for gas compressor cooling in the oil and gas processing industries. A typical 24.4 MW unit operates at 70 bar for both gas/gas and gas/condensate duties.

Recently, Chart-Marston has developed the Marbon heat exchanger (Watton et al [1997]). This heat exchanger is made of stacked and bonded together stainless steel plates. Several configurations are possible. (1) shell and tube or (2) plate fin. So far only small units can be manufactured. The use of such heat exchanger as a chemical reactor is under consideration, and the thermal and hydraulic characterisation is undertaken in the framework of a European funded project.

2.7 Matrix heat exchangers

Perforated or matrix heat exchangers are highly compact heat exchangers and consist of a stack of perforated plates made of high thermal conductivity material such as copper or aluminium, alternating with spacers of low thermal conductivity such as plastic of stainless steel. The pack of alternate low and high thermal conductivity plates are bonded together to form leak free passages between the streams. The main assembly technique adopted is diffusion bonding, more information can be found in Krishnan et al [1997].

Such heat exchangers have been developed for cryogenic and low temperature application (Nilles et al [1993]) and for fuels cells (Ahuja and Green [1998]). These heat exchangers are suitable for a large range of operating conditions, but there is only little information on their thermal and hydraulic behavior. Furthermore, as the heat is transferred by conduction in the plate, the temperature distribution is not homogeneous.

2.8 Flat tube and fins heat exchangers

The concept of flat tube and fins in heat exchangers has been developed in the automobile industry for engine cooling and air conditioning (Cowell and Achaichia [1997], Trauger and Hughes [1993] and Webb [1998]). In such application one of the two fluids is air and the other is either water or an other coolant. The non equilibrium of the heat capacities of the two fluids leads to adopt different enhancement technologies for both fluids. Generally on the air side the surface is finned (plain or louver fins) and on the other side the fluid flows in small diameter channels. The technology is based on assembling aluminium elements either by mechanical expansion or brazing. For conventional applications, the pressure can be up to 20 bar. Recently for car air-conditioning systems using carbon dioxide as coolant, heat exchangers with operating pressure up 140 bar have been manufactured (Pettersen et al [1998]).

2.9 Selection of heat exchanger technology

The selection of compact heat exchangers technology depends on the operating conditions such as pressure, flow rates, temperature but also on other parameters such as fouling, corrosion, compactness, weight, maintenance and reliability. Table 2 summarises the major limits for the different types of compact heat exchangers. In most of the cases, the maximum pressure and temperature cannot be reached simultaneously.

TABLE 2. OPERATING CONDITIONS OF COMPACT HEAT EXCHANGERS

Technology	Maximal pressure	Maximal temperature	Number of streams	Fouling
Aluminium plate fin heat exchanger	80-120 bar	70-200°C	>10	no
Stainless steel plate fin heat exchanger	80 bar	650°C	>2	no
Ceramic plate fin heat exchanger	4	1300°C	2	no
Diffusion bonded heat exchanger	500 bar	800-1000°C	>2	no
Spiral heat exchanger	30 bar	400°C	2	yes
Matrix heat exchanger	1000 bar	800°C	>2	no
Flat tube and Fin heat exchanger	200 bar	200°C	2	no
Brazed plate heat exchanger	30 bar	200°C	2	no
Welded plate heat exchanger	30-40 bar	300-400°C	>2	yes/no
Plate and shell heat exchanger	30-40 bar	300-400°C	2	yes/no
Gasketed plate heat exchanger	20-25 bar	160-200°C	>2	yes
Plastic plate heat exchanger	2 bar	200-250°C	>2	yes/no

TABLE 3. HEAT EXCHANGER SELECTION FOR THE HTR RECUPERATOR

Technology	**Pressure**	**Efficiency***	**Reliability***
Spiral	30 bars	good	good
Plate-fin	80 bars	very good	good
Welded plates	30-40 bars	good	good
Diffusion bonded	500 bars	good	very good

*based on manufacturers information.

3 CONCLUSION

Within the HTR context and due to the high pressure difference for the recuperator (≈ 45 bar) only welded, brazed or diffusion bonded heat exchangers could be used (table 3).

Today, the diffusion bonded heat exchangers with micro-channels appear to be the more promising concept for the recuperator application. In spite of a more important pressure drop, this concept is best rated compared to the other concepts in particular in terms of reliability, mechanical resistance and compactness. This concept has been proposed as alternative solution in the frame of the GT-MHR and PBMR projects.

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