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Compact/Micro Heat Exchangers – Their Role in Heat Pumping Equipment

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Abstract Compact and micro-heat exchangers have many advantages over their larger counterparts, particularly when used to handle clean fluid streams, either single- or two-phase. Probably the most exciting feature of such heat exchangers is their ability to operate with close approach temperatures, leading to high effectiveness. This can be particularly beneficial when the exchangers are used in power-producing or power-consuming systems, where the improved heat exchanger effectiveness can be immediately realised in higher power outputs or reduced power consumption. In the case of heat pumping equipment – the most common examples being air-water or air-air vapour compression cycle heat pumps for domestic heating – this manifests itself in an increased Coefficient of Performance (COP) that reduces CO_2 emissions due to a lower energy input needed to drive the compressor. This paper discusses some of the work carried out in five countries, Austria, Japan, Sweden, USA and the UK, within the IEA Heat Pump Implementing Agreement Annex 33 to identify the heat exchangers that can most benefit heat pump cycles, with a strong emphasis on micro-channel heat transfer. It also presents data on other research relevant to the subject, with an emphasis on the 'micro' size range.

Keywords: Compact heat exchangers, micro-heat exchangers, boiling and condensation, heat pumps.

1. Introduction

During the last two decades there have been substantial developments affecting equipment used within the refrigeration and heat pump industries, brought about largely due to environmental concerns, principally related to vapour compression cycle systems: Firstly, the realisation of the detrimental effect of chlorinated hydrocarbons on the ozone layer led to a quick phase out of these fluids, a process which is now complete in many parts of the world. Secondly, as more focus and concern has been directed towards the issue of global warming, the global warming potential (GWP) of many of the commonly used working fluids, in particular hydrofluorocarbons (HFCs), has been topping the agenda. Thirdly, and discussed later, the materials content of heat exchangers in fan-coil units (and in other heating/cooling units) are regarded rather negatively from the points of view of environmental impact and life cycle assessment[1].

Due to these perceived negative effects on the global environment, parts of the industry as well as parts of the research community and some governmental institutions, in particular in Europe, have suggested the use of natural fluids, meaning primarily ammonia, hydrocarbons and carbon dioxide, as working fluids. All these fluids are suitable from a technical point of view, although each is not necessarily ideal for all applications. However, they all have drawbacks, relating either to flammability or toxicity, or operation at high pressure. If used in public areas, the quantities of working fluid in the systems should therefore be kept as low as possible.

Having the global and local environment in mind, it is clear that future refrigeration and heat pump equipment should have as small as possible internal volume. This conclusion is equally true independently of the refrigerant chosen in the system: With HFCs and other high GWP-fluids a low charge will reduce the total leakage, thus reducing the influence on the global warming. With ammonia, hydrocarbons and carbon dioxide, a low charge will reduce the risks of accidents in case of leaks.

An additional parameter which must be taken into account is the indirect influence on the global warming from any type of refrigeration or heat

[1] See research of Matajaz Prek at the University of Ljubljana, for example, reproduced in *Energy and Buildings*, 36 (2004) 1021-1027.

pump unit. As long as we manage to keep our systems tight these secondary effects caused by the CO_2 emissions connected to electricity production are far larger than the direct effects caused by the leakage of refrigerant. A reduction of charge must thus not be accomplished at the cost of reduced energy efficiency of the system.

Looking at the distribution of the charge of working fluid within a heat pumping system it is quite clear that the dominating part is located either in the evaporator or in the condenser for vapour compression cycle and mechanical vapour recompression cycle units and, where absorption cycle systems may be considered, additionally in the generator and absorber. Reducing the charge is therefore mainly a matter of redesigning the heat exchangers. (A possible exception to this rule is the case of multisplit, direct expansion systems where a large amount of liquid working fluid is circulated through long tubing systems. For this type of system, a first step, it is suggested, should be to redesign to an indirect system, using a secondary fluid to distribute the heating/cooling capacity). To reduce the volume on the working fluid side without decreasing the energy efficiency of the system may seem a difficult task. The heat transfer areas on the two sides of the heat exchanger should preferably not be decreased, as this may increase the temperature difference between the fluids and thus reduce the efficiency.

The obvious solution to this equation is to decrease the channel area cross section, i.e. the hydraulic diameter. Fortunately, a decreased diameter may offer possibilities of increasing the heat transfer coefficients. In single phase flow it can easily be shown that in most instances, for a fixed temperature difference, a fixed pressure drop and given heat- and mass flows, the heat transfer coefficient will increase and the necessary heat transfer surface area will decrease with decreasing tube diameter. For two-phase flow, condensation and evaporation, the analysis is not as simple partly because there are no reliable correlations available for predicting heat transfer and pressure drop for small-diameter channels. However, there are increasing indications that in two-phase flow decreased channel diameter will lead to increased heat transfer rates and thus the possibilities of improving the system performance. Currently, there is uncertainty about the conditions which lead to local dry-out in micro-channels and this makes reliable design for a range of operating conditions difficult at present.

For certain applications small diameter channel heat exchangers have already been implemented, for other reasons than the decrease of working fluid inventory. One area is for cooling of electronics, where active cooling of individual components by fluid channels incorporated into the structure has been discussed for long. As an alternative, cold-plates with mini-channels or mini-channel heat pipes are used for cooling certain types of components. A second area is automotive air conditioning, where extruded multi-channel aluminium tubes have been used for several years, primarily as condensers. There are also some manufacturers who have specific methods of manufacturing heat exchangers with small hydraulic diameters. These producers may target specific applications, such as off-shore gas processing or chemical process intensification (where reduced inventories and reduced footprints are selling points), or they may rely on having customers in different areas, all having specific requirements concerning the heat transfer, which may be met by the compact designs.

Developments in the area of compact heat exchangers (CHEs) are partly driven by demands from industry, e.g. the electronic industry and the chemicals sector. A second reason for the development is the progress in the area of materials science: It is now possible to manufacture small size objects with high precision in large quantities at low cost. We believe that these possibilities have not yet been totally explored for the benefit of the heat pump and refrigeration industry.

Highly relevant to all refrigeration and heat pump systems is the cost of disposal. It is believed that disposal/recycling will be facilitated by employing CHEs in the whole range of heat pump equipment, regardless of cycle type, as the quantities of metals to be disposed of, as well as the fluid(s) within the systems, should be reduced. The energy use in manufacture should also be reduced, reducing the overall environmental impact.

Critical to the success of work aimed at minimizing working fluid inventory (by compact and micro-systems) is the likely demand for heat pumps. In Japan it was expected that the sales of air-water CO_2 heat pumps would reach about 1.8 million at the end of the financial year 2007/8 (IEA Annex Web Site, 2009). The Japanese Government identified the heat pump as an important technology for global warming prevention in its "Kyoto Protocol target achievement plan", and has supported it to the tune of US$578 to date. Even in the UK the heat pump is now accepted as a renewable energy device and while ground source heat pumps have recently been most popular for domestic heating, air-air and air-water systems are becoming increasingly efficient, thanks in part to CHEs.

2. Background to the Annex

Annex 33 was established in 2006 with Brunel University as the Operating Agent, or Annex manager. With a three year timescale, the goals were as follows:

(a) to identify compact heat exchangers, either existing or under development, that may be applied in heat pumping equipment – including those using vapour compression, mechanical vapour recompression and absorption cycles. This has the aims of decreasing the working fluid inventory, minimising the environmental impact of system manufacture and disposal, and/or increasing the system performance during the equipment life, thereby reducing the possible direct and indirect effects of the systems on the global and local environments.

(b) to identify, where necessary propose, and document reasonably accurate methods of predicting heat transfer, pressure drop and void fractions in these types of heat exchangers, thereby promoting or simplifying their commercial use by heat pump manufacturers. Integral with these activities will be an examination of manifolding/flow distribution in compact/micro-heat exchangers, in particular in evaporators.

(c) to present listings of operating limits etc. for the different types of compact heat exchangers, e.g. maximum pressures, maximum temperatures, material compatibility, minimum diameters, etc. and of estimated manufacturing costs or possible market prices in large scale production. It is intended within this context that opportunities for technology transfer from sectors where mass-produced CHEs are used (e.g. automotive) will be examined and recommendations made.

The data are being disseminated by several means, including teaching materials, workshops, and a website – www.compactheatpumps.org

3. The Research within the Annex

Each participating country in the Annex contributes research relevant to the scope that is being undertaken within the country. In the UK, a major EPSRC-funded research programme involving five Universities (led by Brunel) and ten companies, recently completed, on boiling and condensation in micro-channels has provided data on two-phase heat transfer in single and multiple micro-channels that may form the basis of evaporators and condensers in compact heat pumps. Fig. 1 shows bubble formation in the channels (e.g. centre of third horizontal channel from bottom) of a test section at Heriot-Watt University. Channel width and depth are 1 mm.

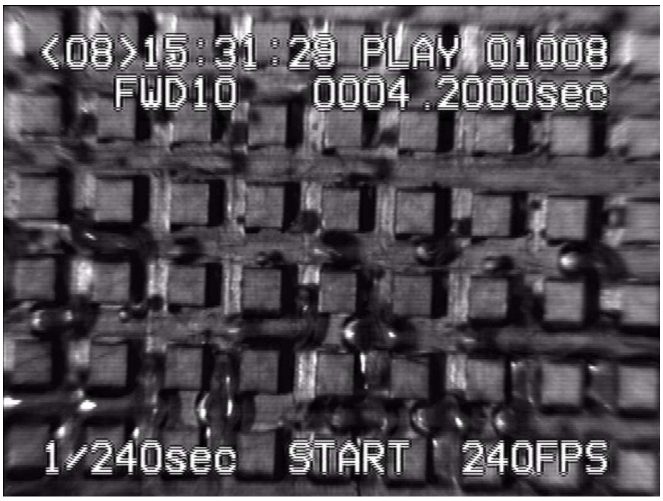

Fig. 1. Boiling in a Micro-Channel Section

Other inputs from the UK team include market data on heat pumps, in particular industrial units where the use of compact heat exchangers in applications where fouling is unlikely to be a problem (some evaporators and distillation columns for example) would allow a breakthrough in the acceptability by the process sector, where payback period is a dominant factor in deciding upon the investment. In the food and drink and petrochemicals sector up to 6% of energy use could be saved by heat pump technology, using open or closed cycle machines (HEXAG. 2006).

Research in the USA was co-ordinated by Prof. Clark Bullard of the University of Illinois. Five projects were contributed, four being from the Air Conditioning & Refrigeration Institute (ACRI) and one from the US Department of Energy. There ranged from the air-side performance of flat-tube heat exchangers to super and near-critical heat transfer of R410A in small diameter tubes. Novel materials for heat exchangers were also investigated, as was void fraction measurement in condensing refrigerants in small diameter tubes. An interesting concept being examined at Oak Ridge National Laboratory and Vanderbilt University is a woven graphite fibre heat exchanger, the fibres forming the extended surfaces on the air-side – see Fig. 2. The use of polymers in heat exchangers was also investigated for heat pumps. As well as being in some instances cheaper than metallic equivalents, their lightness and resistance to corrosion makes them potentially attractive in absorption cycles where materials compatibility may be a problem. Modern fabrication methods permit mm dimension (or less) channels to be formed in polymeric materials and with thin walls the perception of high thermal resistance can be overcome, Fig. 3.

The Japanese inputs are several. At Kyushu University work is concentrating upon the heat transfer characteristics of CO_2 flowing in smooth and micro-fin tubes of diameter 1-6 mm, particularly at supercritical pressures. This working fluid is established in heat pump water heaters, as mentioned above, but is now being examined for the massive domestic air conditioning market. Enhancement factors of over 2 times (from 7 kW/m^2K to 15 W/m^2K) were achieved in grooved tubes.

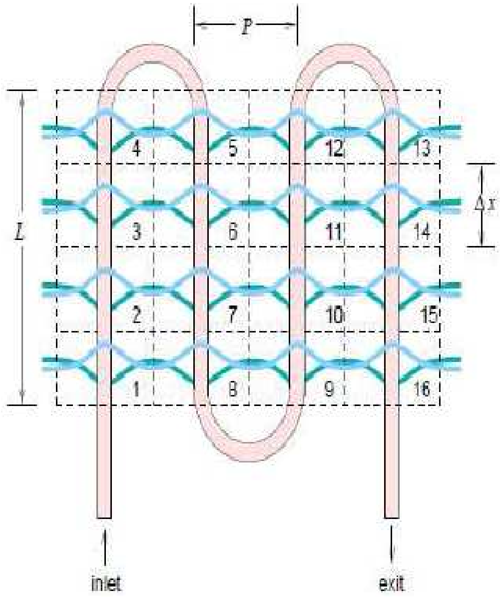

Fig. 2. Woven Graphite Fibre Heat Exchanger. (Annex 33 Web site. 2009)

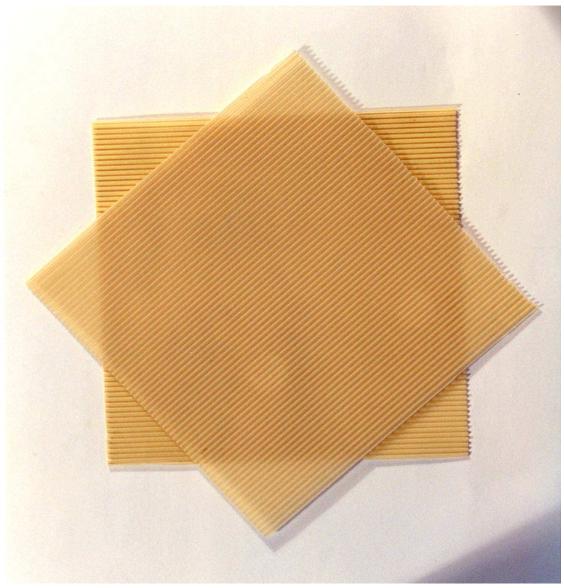

Fig. 3. A Polymer Film CHE made in PEEK at Newcastle University – Channel Hydraulic Diameters are typically 1-2 mm.

A number of novel CHEs have been examined, including one that resembles the Heatric Printed Circuit Heat Exchanger but is designed for lower pressure drops – see Fig. 4.

This is proposed as a condenser in an air-water heat pump, with the CO_2 working fluid condensing in channels of approximately 0.5 mm in height and 1.5 mm wide. Diffusion bonding gives good integrity at high pressures, particularly where legislation requires water to be delivered at over 65°C.

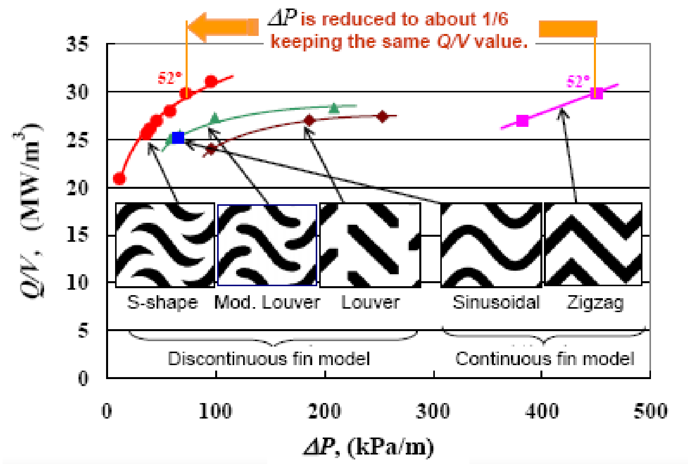

Fig. 4. The PCHE with S-shaped fins (Annex 33 Web site. 2009)

Professor Bjorn Palm at KTH in Stockholm leads the Swedish input to the Annex. He has been examining a number of configurations for enhanced compact heat exchangers, one initiative involving the incorporation of porous surfaces onto the plates of small plate heat exchangers. This has allowed overall heat transfer coefficients in evaporation to be increased by 70-110% over the plain surface. The surface modification was a porous layer of 250 microns thickness, with an average pore diameter of 105 microns and a pore density of 75/mm^2.

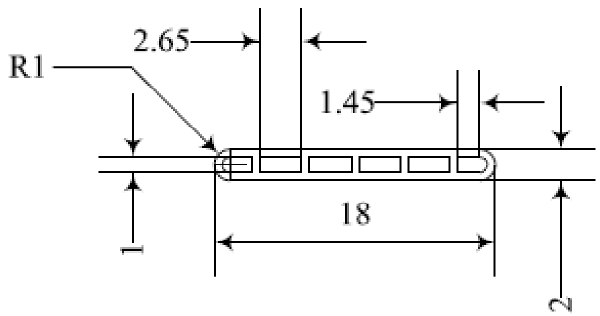

Fig. 5. The Aluminium Channels Investigated at KTH, (dimensions in mm).

The development of multi-port micro-channel heat exchangers in aluminium – see Fig. 5, made possible by the use of modern extrusion techniques, where channel hydraulic diameters of about 1.5 mm can be readily achieved, has allowed reduced fluid inventories and better coefficients of performance.

The absorption cycle heat pump, particularly in commercial/industrial-sized applications, is often a collection of typically four shell and tube (large) heat exchangers, as shown in the unit at British Gas Research Laboratories in Fig. 6. For decades it has been an ideal candidate of process integration and process intensification!

The research at Arsenal in Austria includes the study of new CHE concepts for absorption heat pumps. Initially directed at low duties, the features include modular designs that would be suitable for automated manufacturing processes. Surface treatments and coatings may be key features contributing to enhanced performance.

4. Why Are We Interested – From the System Point of View?

Much of the work directed at producing CHEs, whether we call them compact, micro- or nano-, is associated with heat transfer enhancement that has a considerable influence on the efficiency of the SYSTEM we are using such heat exchangers in.

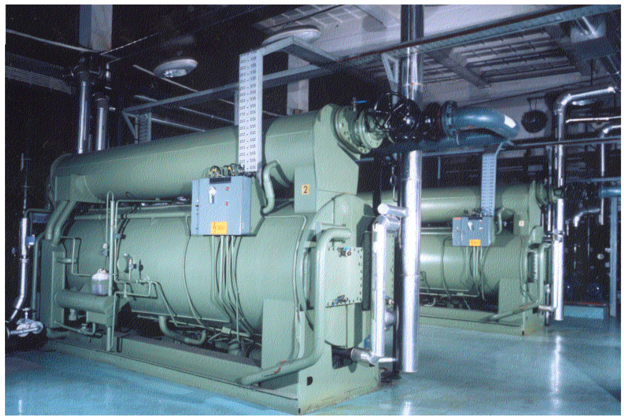

Fig. 6. An Absorption Chiller showing its Size (about 3.5 m high) and Associated Pipework.

Consider the three principal types of equipment which use two-phase heat exchangers as follows:

- Power-producing systems, such as those based on the Rankine cycle
- Power-consuming systems, such as vapour compression refrigeration plant and heat pumps

- Heat-actuated systems such as absorption heat pumps (and a cycle we have not discussed – adsorption units)

For **power-producing systems** heat transfer enhancement can reduce the boiler and/or condenser surface for a given duty, i.e. for a specific turbine output. Alternatively, by adding enhancement to the existing boiler and condenser, for example using tube inserts, the turbine output might be increased – a form of 'debottlenecking'. Closer approach temperatures in the condenser and evaporator result in higher cycle efficiencies.

In the case of **power-consuming systems** three possible benefits can be realised:

- The heat transfer area can be reduced for a given compressor power
- The evaporator duty can be increased for a given compressor lift
- The compressor power can be reduced for a given evaporator duty (due to closer approach temperatures).

In **heat-actuated systems**, again three possible benefits exist:

- The heat transfer area can be reduced for fixed operating temperatures

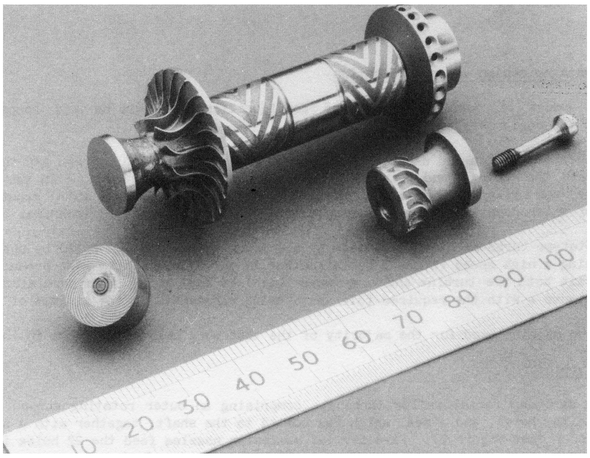

Fig. 7. The Glynwed Rankine-Rankine Cycle Heat Pump (Reay et al. 1999).

- The heat exchanger capacity can be increased, while keeping the surface area constant
- The log mean temperature difference (LMTD) can be reduced for a given surface area, and in this case the thermodynamic efficiency of the process can be improved.

The above examples show that enhancement can benefit heat pumping processes involving heat exchangers in many ways. Each route chosen has its own trade-offs, and the comparison of benefits can be complex. Nevertheless, their potential is considerable.

The selection of an appropriate enhancement technique must take into account the nature of the fluid stream(s) involved. For example, some enhancement methods, particularly those involving fine surface features, are susceptible to contaminants which could reduce the effectiveness. Heavily fouled streams, or those containing oil, such as a refrigerant circuit using an ineffective oil separator, would not be ideal candidates. Some incur a pressure drop penalty.

The heat exchangers, as far as vapour compression cycle units are concerned – and these form the vast majority of heat pumps – represent typically 50% of the major components, including the compressor and the drive unit (commonly an electric motor).

Attempts to minimize the size of the other parts – in particular the compressor, have shown some success, at least in research programmes. Some 30 years ago Glynwed developed a Rankine-Rankine cycle heat pump using one of the CFC refrigerants available at the time, the turbo-compressor unit being shown in Fig. 7. The application was domestic space conditioning.

One concept proposed by Heriot-Watt University, Edinburgh (Reay et al. 1999) was a water-water heat pump employing a rotary vane compressor embedded in a printed circuit-type heat exchanger. The unit was designed to operate using R134a with evaporating and condensing temperatures of $-4^{o}C$ and $60^{o}C$ respectively, an output of 3 kW and a COP of 3. The unit (excluding water-side headers, water pumps and compressor motor) would occupy a block 25 mm x 700 mm x 200 mm, or 0.0035 m^3. Interestingly, the unit here has a similar duty per unit volume to that of an absorption cycle unit (ammonia/water) that was investigated by Heriot-Watt University and Absotech in Germany based upon the Hesselgreaves compact heat exchanger surface, (Hesselgreaves, 1997). This design had a 100 kW cooling duty using ammonia and water working fluid pair, and a core size of 1000 mm x 550 mm x 200 mm, or 0.11 m^3, (Reay et al. 1998).

Since the proposals reported in 1999, others have adopted similar strategies in order to 'compress' heat pumping/refrigeration cycles. The ARCTIC project at the University of California is directed at chip cooling in microelectronics, and necessarily adopts a rotary compressor (as selected by Kew at Heriot-Watt in 1998 – see above), in this case a Wankel type that is projected to give a compression ratio of 4.7:1, (Heppner et al. 2007).

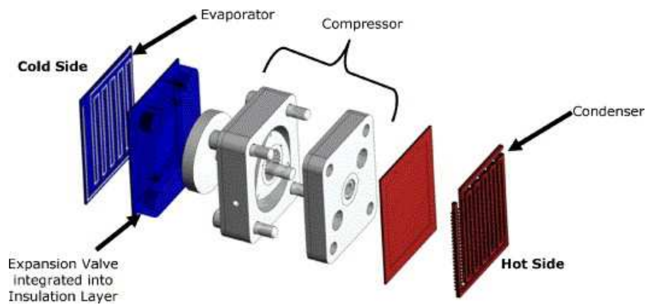

Fig. 8. The ARCTIC Micro-heat pump/refrigerator (Heppner et al. 2007).

The schematic of ARCTIC is shown in Fig. 8. By using MEMS components within the unit, and a compressor with a 'footprint' about the size of an Intel Pentium 4 chip (25mm x 30mm) the researchers indicate that a theoretical COP of 4.6 is achievable, with a cooling capacity of 45W, a temperature difference of 40K and a compressor speed of 1000 rpm.

There are a number of other instances where micro-technology has been studied for heat pumping duties. These serve as examples of process intensification (Reay et al. 2008) with substantial practical application potential, and secondly also allow an energy-efficient concept to be used for heating and/or cooling micro-engineered processes. (It is interesting to note that passive and active cooling methods for computer chips are the subject of intense patent activity, and the successful techniques coming to the market auger well for the 'lab on a chip;' concept and its thermal control. These go beyond the relatively common thermoelectric devices).

Leading laboratories for micro-heat pumps include Battelle in the USA and SINTEF in Norway, (Munkejord et al. 1999). The work at SINTEF on devices with main dimensions of the order of a few cms, with trapezoidal channels of 0.5 mm width concentrated on the heat exchangers and their performance. Illustrated in Fig. 9, the micro condenser so constructed showed that a heat flux of 135 kW/m^2 based on the refrigerant-side area was possible. The overall 'U' value was 10 kW/m^2K.

Several aspects of micro electro-mechanical system (MEMS) technology have been investigated for refrigerator/heat pump technology, extending to compressor concepts, which are as yet untried. A few of the fundamental principles for converting electricity into mechanical displacement/forces to create displacement could be envisaged as the basis of a compressor – some of the aspects of microfluidics involving electric field may also come into play. In the North East of England Newcastle University is leading an EPSRC project with Oxford and LSBU on a vapour compression cycle unit for cooling processors.

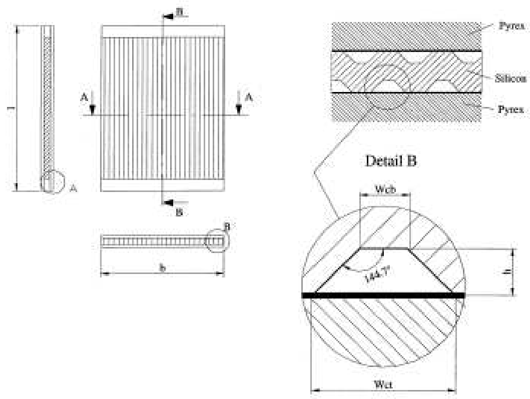

Fig. 9. The SINTEF Heat Exchanger Design for use in Micro-heat Pumps (Munkejord et al. 1999).

5. Conclusions

The efficiency of heat pumps is improving, thanks in part to effective heat exchangers. The use of compact and micro-heat exchangers is also leading to cost and size reductions that will hopefully accelerate their penetration into space conditioning and process heating applications. When this occurs on a large scale, the heat pump will be seen to be one of the most effective energy-saving devices in applications ranging from our home to petrochemical plant. Outputs from Annex 33 that will be generally available should assist this market penetration.

6. Acknowledgements

The authors acknowledge with thanks the considerable inputs of the partners in IEA Annex 33, whose papers may be seen on the project web site – see the reference list.

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