Annex 33

Compact Heat Exchangers in Heat Pumping Equipment

Executive Summary

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Production

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1. Preface

This project was carried out within the Heat Pump Programme, HPP which is an Implementing agreement within the International Energy Agency, IEA. The full report of Annex 33 is available for downloading at the Heat Pump Centre website, www.heatpumpcentre.org.

2. Introduction

The objective of this Annex was to present a compilation of possible options for compact heat exchangers, used as evaporators, condensers and in other roles in heat pumping equipment. The aim is to minimise the direct and indirect effect on the local and global environment due to operation of, and ultimate disposal of, the equipment. The Annex report relates specifically to design data for compact heat exchangers used in heat pumping systems at the process/large commercial level.

The Annex involved five countries – Austria, Japan, Sweden, the United States and the United Kingdom, the latter acting additionally as Operating Agent. The Annex ran for three years, the final Annex meeting being held in the UK in September 2009.

3. Background

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.

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

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 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.

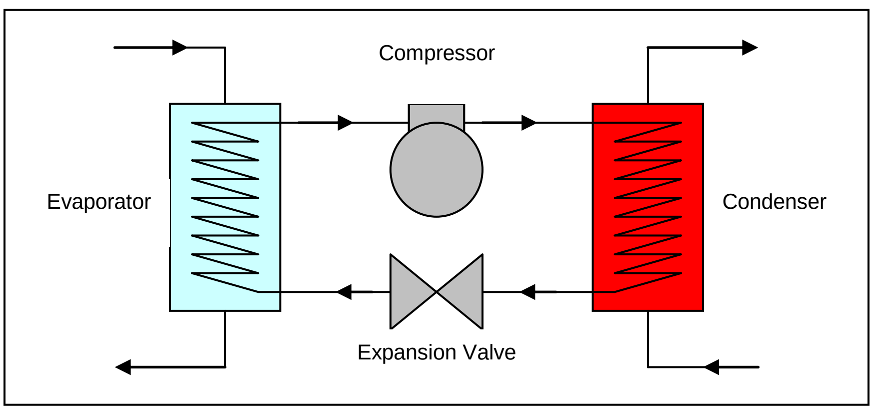

Figure 1: Even in the simplest heat pump cycle, heat exchangers can govern equipment volume

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 and thus the possibilities of increasing the system performance.

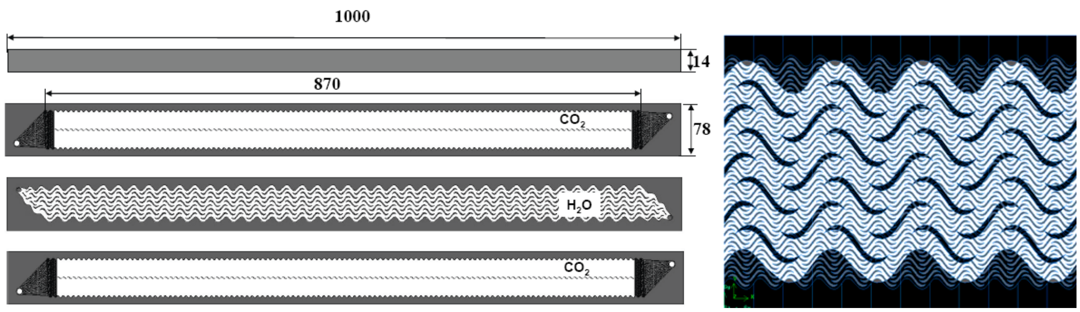

Figure 2: The Japanese Microchannel Heat Exchanger (MCHE), a development of the Printed Circuit Heat Exchanger (PCHE), is used in a heat pump for heating domestic hot water using CO2 as the working fluid. The figure to the right is a magnification of the channel layout on the water side.

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 multichannel aluminium tubes have been used for several years, primarily as condensers[2]. 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 are a selling point), 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

[2] The development of micro-channel finned heat exchangers for residential split air conditioners was described recently by Salvatori Macri of Carrier S.p.A. at the AiCARR Meeting in Milan in March 2006. Charge reduction was highlghted as one major benefit.

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.

4. Goals of Annex 33

The principal goal of the Annex was to identify compact heat exchangers[3], 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.

A second goal was 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 was an examination of manifolding/flow distribution in compact/micro-heat exchangers, in particular in evaporators.

A third goal was 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. Much of these data are presented within the Annex 33 Final Report.

The outcomes of Annex 33, which was concerned with compact heat exchangers (CHEs) in heat pumping equipment have been many, quite diverse in their nature and comprehensive.

5. Features of Compact Heat Exchangers

Compact heat exchangers are used in a wide variety of heat pumping equipment, including the plate heat exchanger where liquids are being heated or cooled, and air-cooled heat exchangers with high density finned surfaces, to maximize the surface area/unit volume for effective heat transfer, where air-side fouling is not a problem.

However, in every application there may be a number of factors affecting, ultimately, the long-term satisfactory operation of compact heat exchangers. Having decided upon the type of heat exchanger to be used in a particular situation, (an exercise which will have already considered some aspects of fouling), the installation of the unit must be carried out, and guidance given to those involved in the operation and maintenance of the unit.

[3] A selection of CHEs and their applications may be found in an IEA-CADDET Publication: Learning from Experiences with Compact Heat Exchangers. CADDET Analyses Series No. 25, June, 1999.

Fouling, and to a lesser extent corrosion, and their minimisation remain key priorities during the life of many heat exchangers, particularly those in arduous process industry duties, and these aspects should never be neglected during the life of the unit.

It should of course be noted that the majority of the fouling in heat exchangers in heat pumps, particularly vapour compression types, will take place on the process side(s) of the heat exchangers and the working fluid itself should remain relatively clean. Bear in mind that wear can lead to metallic particles from bearings, etc., and the oil used as a lubricant, if in the working fluid, can affect the heat transfer characteristics.

The discussion is targeted towards process applications, although some of the principles are relevant to all applications of compact heat exchangers. Domestic heat pumps will suffer from air-side fouling, possibly fouling due to dirty water, and of course ground coils (not really 'compact') do have a 'fouling resistance' associated with their contact with the soil/earth.

The factors to be considered are set out in the following order:

1. Specification/purchase
2. Installation
3. Commissioning
4. Operation
5. Maintenance:
    a. General factors
    b. Fouling & corrosion

Where the external environment affects the CHE selection it may be best to consider in the first instance the exchanger in isolation, rather than as a heat pump component. It is often compared with a shell and tube heat exchanger – in many instances of their use, the CHE may well be replacing an earlier plant/process design that incorporated the larger heat exchanger variant.

6. Generic Advantages of Compact Heat Exchangers

The main benefits of using compact heat exchangers in the context of heat pumping equipment are:

- Improved heat exchanger thermal effectiveness.
- Closer approach temperatures.
- High heat transfer coefficients and transfer areas per exchanger volume.
- Smaller size.
- Energy savings.
- Reduced fluid inventory.
- Process intensification.

These technological advantages can be converted into reduced operational and capital costs, and conserve energy, compared to shell and tube units, and are discussed below.

Improved Heat Exchanger Thermal Effectiveness: A major advantage of most compact designs is their greater efficiency or thermal effectiveness (E). The effectiveness of a heat exchanger can simply be expressed as the ratio of the actual heat transfer to the maximum possible heat transfer. The effectiveness is a function of the heat capacity of the fluid streams, the overall heat transfer coefficient and the area of heat transfer surface.

The benefits of improved heat exchanger efficiencies are described below. One advantage of a higher effectiveness - a closer approach temperature difference - is a beneficial effect on the relative position of the hot and cold composite curves utilised in a process integration analysis. This can lead to significant energy cost savings in process heating and cooling duties.

$$E = \frac{\dot{M}_c Cp_c (T_{c,out} - T_{c,in})}{(\dot{M}Cp)_{min} (T_{h,in} - T_{c,in})}$$

(In this equation $\dot{M}$ is mass flow, Cp specific heat and T temperature (K). Suffices are c = cold stream, h = hot stream, in = into the exchanger, out = leaving the exchanger, min = minimum value for a stream.)

For shell and tube heat exchangers, the thermal effectiveness (E) is typically 0.75. Values in excess of 0.95 are economically possible with compact heat exchangers - up to 0.98 for PCHEs (see the Japanese contribution in Appendix 3 if the Full Report).

Closer Approach Temperatures: Approach temperature is an alternative measure of heat exchanger performance. As the outlet temperature of the cold stream $(T_{c,out})$ approaches the inlet temperature of the hot stream $(T_{h,in})$, the thermal effectiveness (E) increases.

A shell and tube heat exchanger with an effectiveness of 0.75, heating a single phase fluid from 10°C with a hot source stream at l00°C, will give a cold stream outlet temperature of 77.5°C: that is, an approach temperature of 22.5°C.

A compact heat exchanger with an effectiveness of 0.95, (achievable with current designs of plate heat exchangers), used for the same application, would give a cold stream outlet temperature of 95.5°C: that is, an approach temperature of only 4.5°C.

Compact heat exchangers have:

- High heat transfer coefficients due to the small hydraulic diameter of the flow passages.
- High heat transfer surface areas for a given volume of heat exchanger. Typically, compact exchanger area/volume ratios may be up to an order of magnitude greater than those of shell and tube exchangers depending on the exchanger type. The new generation of ‘micro’ heat exchangers can even approach a two orders of magnitude reduction.

In many instances the high heat transfer coefficient is frequently achieved without excessive pressure drop.

An arrangement of shell and tube heat exchangers in series could provide high heat transfer areas and the effectiveness of such an assembly could thus be made as high as required. However, the greater area/volume ratio and high heat transfer coefficients of compact heat exchangers give a high effectiveness with a much smaller overall volume. A cost-effective heat exchanger with a high effectiveness can therefore be achieved with a compact design.

Smaller Size: Obvious from the above discussion, another advantage of compact heat exchangers is their smaller physical characteristics for a given heat transfer duty compared to most shell and tube heat exchangers.

This has benefits that extend well beyond the heat exchanger itself, including, for example, reduced support structure and more convenient location (particularly when installed on a 'greenfield' site). Obviously in restricted space applications, reduced size and weight are important selection criteria. Also, the additional space needed to remove the tube bundle from the shell of a shell and tube unit should not be overlooked; the equivalent space required on a compact heat exchanger with a removable core is proportionally less.

Compact heat exchangers, particularly when their total installed cost is considered, tend to be significantly cheaper than their conventional counterparts. While this may not always be the case when low-cost metals can be used, the benefits of compact heat exchangers are much more apparent when the heat exchanger has to be made from an expensive material such as nickel or titanium. Here the cost per kilogram of raw material dominates the cost of the exchanger, and often adjacent ancillaries. Some years ago a leading heat transfer engineer at a major oil & gas company pointed out that the installed costs of CHEs were typically two times their capital cost, while for shell and tube units, installation was up to five time the heat exchanger purchase price.

Energy Savings: The ability of compact heat exchangers to operate with smaller driving temperature differences between streams means that it is possible to reduce the power requirements of plant items such as refrigeration compressors that were previously sized for the greater temperature differences required with shell and tube heat exchangers. The principal driver of IEA HP Annex 33 has been energy savings, coupled with size and cost reductions in heat pumping systems.

Reduced Fluid Inventory: Compact heat exchangers operate with much lower fluid inventories (the 'hold-up') than many conventional heat exchangers.

The implications of lower fluid inventories include:

- Safer operating conditions when handling hazardous fluids – important for ammonia, for example.
- Reduced volume when handling highly valuable products – as the costs of refrigerants/working fluids rises, the reduced inventory in CHE-based systems becomes increasingly attractive.

It should be noted that the low hold-up of compact heat exchangers, compared to conventional designs, allows them to react quickly to changes in conditions. This should be taken into account when designing associated control plant and other upstream equipment, but in some process heat pumping applications a lower response time can have a positive effect on, for example, product quality.

Process Intensification: Process intensification has various definitions, but is generally associated with active (and in the case of many CHEs, passive) heat and mass transfer enhancement that allow one or two orders of magnitude reduction in the size of equipment.

The most radical (to date) use of process intensification in heat pumping equipment is the Rotex – more recently known as Rotartica – rotating absorption cycle heat pump/chiller/air conditioning unit. This is being trailed in Spain.

7. Conclusions

The objective of this Annex was to present a compilation of possible options for compact heat exchangers, used as evaporators, condensers and in other roles in heat pumping equipment. The aim of the work was to highlight technologies and techniques to minimise the direct and indirect effect on the local and global environment due to operation of, and ultimate disposal of, the equipment.

The outcomes of the Annex consist of a wide variety of data ranging from fundamental research on boiling in narrow channels to guidelines for selecting and using CHEs in heat pumping systems. There are considerable market data available within the Report and the cited references, and a number of novel heat exchanger concepts, including the use of new materials and the application of process intensification methods, should allow equipment manufacturers in the future to achieve the Annex aim.

Particular aspects that it is considered worth highlighting in the Conclusions are:

1. The increasing interest in and use of, CO_2 as a working fluid. This has interesting implications in terms of the equipment used and the concepts for heat pumping that might be applied – see particularly the inputs from Austria and Japan.
2. The growing market for domestic heat pumps, where efficiency, arising in part out of the increased use of CHEs, is critical to further sustained market growth, particularly in countries where heat pump use has been slow to materialize.
3. The vast portfolio of research on heat transfer and fluid dynamics in narrow channels in CHEs. The research highlighted in Sweden, Japan and the USA are of particular note.

4. The role heat pumps could play in industry, where reduced payback times could be aided by CHEs. The UK study highlights the market possibilities.
5. There is a need to educate the heat pump industry in the use of CHEs, their merits and limitations, and the types that are available. The use of new materials, as indicated in some of the research in the USA, could reveal new opportunities.

The project has brought together many experts in the heat pump/CHE field and the Annex Report will, it is believed, be a major and constructive source of data for those interested in using CHEs in heat pumping equipment.

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