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STATUS OF ENHANCED HEAT TRANSFER IN SYSTEMS WITH NATURAL REFRIGERANTS

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ABSTRACT

Global environmental and energy concerns have prompted the heating, ventilating, air-conditioning and refrigeration (HVAC&R) industry to re-visit the use of natural refrigerants. Nearly all natural refrigerants have superior transport properties as compared to synthetic refrigerants; however, the drawback with natural refrigerants has been their toxicity and flammability with an exception of carbon dioxide. In order to overcome this hurdle it is essential that enhanced surface methods be developed and introduced to reduce the refrigerant charge in a system. Halocarbon industry has expended enormous amount of time and money in developing ultra-high efficiency heat exchangers. This experience and knowledge is available and could be applied in developing efficient exchangers for natural refrigerant applications. This paper presents an over view of the status of natural refrigerants and the trends in development of compact and low-charge systems.

NOMENCLATURE

c_p	specific heat, J/kg-K
G	mass flux, kg/s-m^2
i'_{fg}	latent heat, J/kg
Pr	Prandtl number
Re	Reynolds number
β	chevron angle
μ	viscosity, N-s/m^2
ρ	density, kg/m^3
σ	surface tension, N/m
subscripts	
l	liquid phase
v	vapor phase

INTRODUCTION

The depletion of ozone layer and the global warming has left a marking impression on the business of air-conditioning and refrigeration. Various international treaties and protocols have left the industry with few choices. The trend seems to be moving in the direction of complete ban on hydrochloroflourocarbons (HCFC) and hydroflourocarbons (HFC). According to the European Regulation EC2037/2000 the sale of virgin HCFCs which includes R-22, the work horse of HVAC&R business will be prohibited as of January 1, 2010. This ban will also be applicable to the storage of virgin HCFCs (excluding machinery itself). During January 1 2010 and January 1, 2015 operators will only be allowed to use recycled or reclaimed HCFCs. Thereafter, sale and/or storage of recycled or reclaimed HCFCs will be prohibited. Operators will be required to keep a strict record of inventory with equipment containing a charge of 3 kg or more. The goal is to strive for suitable refrigerant with negligible Ozone Depletion Potential (ODP) and a Global Warming Potential (GWP) of less than 150. Most HFCs have low ODP; however, their GWP is much higher than 150 with the exception of HFC-410a. Currently the automotive industry is analyzing an olefin based refrigerant HFO-1234yf (hydrofluoro-olefin) which has a single digit GWP. Since it is mildly flammable, it would be classified under ASHRAE safety class A2.

In view of the current situation it is apparent that the HVAC&R industry is seriously looking into an expanded use of natural refrigerants. However, there are some impediments to this; most prominent are the flammability and toxicity issues. To reduce the effects of these issues the industry must strive for ways to reduce the refrigerant charge in a system. One way to achieve this would be to devise evaporators, condensers and other auxiliary heat exchangers with enhanced surfaces. Recently there has been some activity in research and development in the subject area. There are basically three lead candidates in the category of natural refrigerants:

- Ammonia
- Carbon Dioxide
- Hydrocarbons

The following brief note on each of these refrigerants is directly taken from a recent ASHRAE position document [1].

Ammonia

Ammonia is the most important of the natural refrigerants because of its longstanding and widespread use in food and beverage processing and preservation, and because of its growing adoption in HVAC chillers, thermal storage systems, process cooling and air conditioning, district cooling systems, supermarkets, and convenience stores. Since the middle of the nineteenth century there have been many changes in types of refrigerants, but ammonia is unique because it has seen continued use over this 150 year period.

Ammonia has ODP and GWP equal to zero. It has inherently high refrigeration system energy performance, excellent thermodynamic properties, and high heat transfer coefficients. In a vapor state it is lighter than air. It is easily detected by smell, or by a variety of electrochemical and electronic sensors, and is readily available at a relatively low price. Less than 2% of all ammonia commercially produced in the world is used as a refrigerant; however, ammonia enjoys low cost due to the large volume of production for use as a fertilizer.

The primary disadvantage of ammonia is its toxic effect at higher concentrations (i.e. well above 300 ppm); however, this risk is somewhat mitigated by its pungent smell alerting humans of its presence since even at lower concentrations (5 ppm) it is self-alarming in the event of a leak. Ammonia is classified as, “moderately flammable” in air when its concentration ranges between 16% and 28% (weight); and it is not compatible with copper and copper alloys.

In some jurisdictions, ammonia refrigerating systems are subject to legal regulations and standards because of personnel safety considerations. These do not necessarily present additional barriers because legal regulations, proper maintenance and training of personnel are required for other refrigerants as well. Furthermore, the use of fluorocarbon refrigerants is discouraged in many countries with imposition of environmental legislation and taxes, and uncertainty concerning the Kyoto Protocol consideration. If the regulations and standards are applied in practice, and if suitable training for maintenance personnel is provided, then danger from ammonia use is no different from that of most other refrigerants.

Ammonia provides useful cooling across the range of temperatures, from air-conditioning to low temperature applications. Some air-conditioning systems with ammonia chillers have recently been installed in commercial and public buildings. These units are currently more expensive than fluorocarbon-based chillers, but the price difference is expected to reduce as production volumes increase. A semi-hermetic ammonia compressor is already on the market and will be applied in chillers and in factory-packaged refrigeration units which are used commonly in ice plants and smaller food processing and storage facilities. In order to reduce the potential for ammonia leakage, compact refrigerating units are built, fully sealed and tested in factories, and can be supplied with a charge of less than 50 kg of ammonia for 1000 kW cooling capacity. Lastly, in large industrial systems where there is a need for low temperatures (-30 to -50°C) ammonia has been used in cascade refrigerating systems with CO_2.

Carbon dioxide

Like ammonia, carbon dioxide was also used in the mid- to late-nineteenth century, particularly on board ships and in shops and theatres where the smell of ammonia was not acceptable. However, as ammonia system safety and efficiency improved at the beginning of the twentieth century carbon dioxide systems became less common. With the introduction of fluorocarbons in the 1930s carbon dioxide fell out of use by the 1950s. The low toxicity, non-flammability, zero ozone depletion potential and low global warming potential have attracted the attention of system designers beginning in the early 1990s when alternatives to chlorofluorocarbons (CFC) were being sought. Since then, carbon dioxide has found widespread acceptance in the full range of vapor-compression systems, from low temperature freezers to high temperature heat pumps. It has also been widely used as a secondary refrigerant, offering significant improvements in efficiency compared with traditional water, glycol or brine systems.

One major difference between carbon dioxide and other refrigerants is in its pressure/temperature characteristic because the pressures experienced are approximately ten times higher than those in ammonia or R-404a systems. This high pressure requires special equipment designs, but it also offers many advantages over other refrigerants. The high pressure results in high gas density, which allows a far greater refrigerating effect to be achieved from a given compressor. It also produces very small reductions in saturation temperature for a given pressure drop allowing higher mass flux in evaporators and suction pipes without efficiency penalties. This effect is particularly noticeable at low temperatures (-30 to -50°C), which is why carbon dioxide systems perform so well under these conditions. Exceptionally good system performance has been noted in low temperature plate freezers and multi-chamber blast freezers where improvements in efficiency and reductions in freezing time have been reported.

When the pressure is raised above the critical point (7.3773MPa) it is not possible to condense carbon dioxide. Under these conditions heat rejection is achieved by cooling the very dense gas which results in a temperature glide effect. This has been used to great advantage in water-heating heat pumps for a range of applications from domestic to industrial. These trans-critical heat pumps are particularly efficient when the incoming water is low temperature, for example from the cold water supply. They are less effective over a small temperature range, for example in central heating systems.

The unusual fluid properties of carbon dioxide, including its high density and low critical point, make it particularly well suited for cooling very dense heat loads, such as those found in Information Technology (IT) applications like blade servers and trader rooms. The optimal temperature for transferring heat to carbon dioxide is 14°C, which happens to be exactly the evaporating temperature required for IT cooling in order to avoid dehumidification. In comparison the optimum temperature for R-134a is 77°C, and at 14°C the heat transfer capability of R-134a is only one-sixth of carbon dioxide.

Carbon dioxide is proposed as a good alternative for car air-conditioning. The German Association of the Automotive Industry (VDA) has confirmed the joint decision of the German car industry to choose carbon dioxide for the next-generation of mobile air conditioning by 2011.

Today there are many trans-critical carbon dioxide systems in supermarkets. For about 90% of the year the Coefficient of Performance (COP) of systems with carbon dioxide is higher than in HFC systems. This is the reason that it is an attractive choice for beverage cabinets and vending machines.

Hydrocarbons

In nature, hydrocarbon refrigerants are constituents of oil and natural gas. Hydrocarbon refrigerants have excellent environmental, thermodynamic, and thermo-physical properties, however they are highly flammable. As a result of these factors, hydrocarbons are the molecular basis for the halocarbon refrigerants wherein some or all of the hydrogen molecules have been replaced by halogens such as chlorine, fluorine, and bromine which reduce flammability but can cause unwelcome effects on the environment.

Hydrocarbon refrigerants provide a range of boiling points with applicability from cryogenics to air-conditioning. In the past hydrocarbon refrigerants have had limited applications primarily within the petrochemical industry to provide industrial chilling and process refrigeration. With the phase out of the CFCs, hydrocarbon refrigerants are entering into new arenas. One of the first uses has been as a small quantity constituent in halocarbon blends to provide enhanced thermo-physical properties, such as oil miscibility. For the last decade in the European and Asian countries, the commercial market for systems using hydrocarbon refrigerants has been growing as a result of concerns about the environmental consequences of the halocarbon refrigerants. Examples of commercially available equipment using hydrocarbon refrigerants are:

- systems with small charges including domestic refrigerator/freezers and portable air conditioners,
- stand-alone commercial refrigeration systems including beverage and ice-cream machines,
- as the primary refrigerant in centralized indirect systems for supermarket refrigeration,
- transport refrigeration systems for trucks, and
- chillers in the range 1kW – 150kW (0.3 – 40 tons of refrigeration)

The hydrocarbons most commonly used as refrigerants are:

Methane	R-50
Ethane	R-170
Propane	R-290
Butane	R-600
Isobutane	R-600a
Ethylene	R-1150
Propylene	R-1270

HEAT TRANSFER ENHANCEMENT

There are several types of enhancement techniques [2]. The two basic categories are:

- Passive
- Active

In a passive technique heat transfer enhancement is achieved by changing the surface structure. In an active technique external influence such is momentum, electric or magnetic force is applied. The concept of heat transfer enhancement has been applied to heat exchangers for several decades; however, it has been limited to halocarbon refrigerant applications. Since ammonia did not play any role in the air conditioning business, there was practically no development in this field. Moreover, halocarbons are compatible with copper and copper alloys; hence, it is easy to work with copper than materials that are compatible with ammonia, such as carbon steel, stainless steel and titanium.

The subject of ammonia heat transfer enhancement has shown some momentum since the early 1990s. But the progress has not been monumental for reasons mentioned above. Very few companies in this business have taken the initiative to probe into the potential use of high efficiency tubes. Ammonia related enhanced heat transfer research has also been limited. In the past ten years, less than five research projects have been undertaken by ASHRAE. Similarly, limited research activity has been reported in Europe and Asia. Literature search on the subject indicates less than hundred publications which is extremely low as compared to enhancement work related to halocarbons.

Why Heat Transfer Enhancement with Natural Refrigerants?

All natural refrigerants have superior thermodynamic and transport properties as compared to synthetic refrigerants; however, one important aspect where the natural refrigerants with exception to carbon dioxide, lag behind is the toxicity and flammability issue. Therefore, in order to reduce that element of these two factors, the advocacy for compactness becomes clearly evident. The smaller the heat exchange equipment the lower will be the refrigerant charge and thus less potential for hazard.

How to Reduce the Hazard Factor?

There are fundamentally two ways to handle this issue:

- compactness of heat exchange equipment
- reduction of refrigerant inventory

The ideal option would be to combine both of the above.

RECENT DEVELOPMENTS IN SHELL AND TUBE TECHNOLOGY

Enhanced surface tubes have been used successfully in various applications on a limited scale with natural refrigerants. It is important to select enhancement according to the need of a particular application, e.g., it is not wise to apply enhancement on ammonia side while the controlling side is the process side. Hence, preliminary screening of individual thermal resistances is very critical.

The most widely used natural refrigerant has been ammonia. The pressing issue related to ammonia has been its non-compatibility with copper and copper alloys. The HVAC industry has scaled major strides in advancing the enhanced surface technology for use in halocarbon systems. In this respect the carbon dioxide and hydrocarbon based heat exchangers can take advantage of these developments and effectively utilize these enhanced surface tubes in the shell and tube business, thus rendering smaller and compact heat exchangers.

Enhancement Variation in a Flooded Tube Bundle

In a United States patent Ayub [3] has disclosed a flooded evaporator with various types of enhanced tubes along the bundle height. It has been observed that enhanced surface tubes cause high vapor generation which could become so intense that it causes high vapor-rich zone in the upper section of a tube bundle. Higher void fraction is not desirable since it starves the tubes of liquid refrigerant and in turn affects the performance of the evaporator.

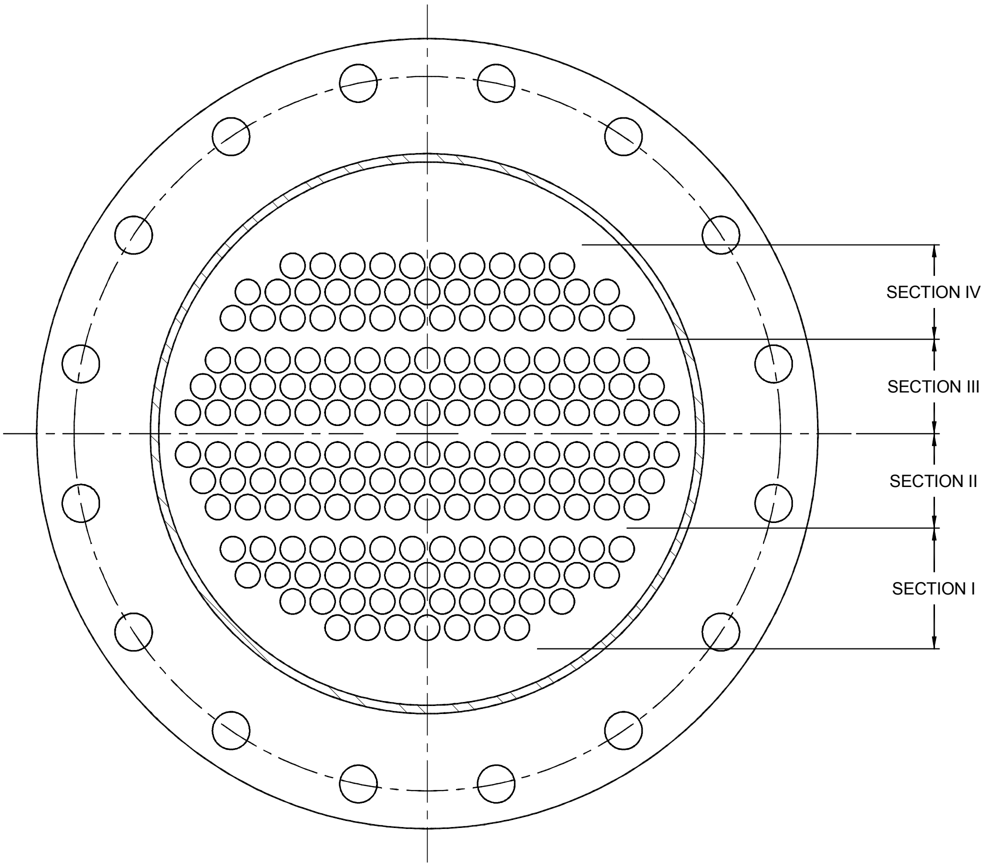

Figure 1 Different type of tubes in different sections of a flooded tube bundle

This patent propose to utilize various type of tubes appropriately selected along the height of the tube bundle, with high efficiency tubes having strong nucleate boiling characteristics in the lower section, i.e., Section I as shown in Fig. 1, followed by tubes with moderate nucleate boiling characteristics in Section II, still another suitable kind of tubes in Section III and even plain tubes (if required) in Section IV. Depending on the size of the tube bundle, these tubes could then be selected accordingly. This invention results in a lower cost by replacing the enhanced tubes in the top section with the less expensive plain tubes. It also results in highly optimized evaporator with no parasitic losses and low refrigerant charge.

In a case study of ammonia flooded evaporator brine (40% propylene glycol) was to be cooled for use in a major food plant in the United States. Initially, shell and plate exchangers were selected; however, due to mechanical integrity and regulatory issues, it was decided to replace them with shell and tube flooded. Since the skid package was in place, fitting shell and tube in an existing limited space was a challenging task.

A conventional flooded shell-and-tube with plain surface carbon steel tubes would have been too large to fit in an existing limited space. Hence, the various-tube bundle concept was adopted. After careful evaluation and intense two-phase flow modeling, it was decided to use three different types of enhanced tubes along the height of the tube bundle in a three-pass chiller. Tubes with high nucleate-boiling characteristics on the outside and enhanced surface on the inside (Fig. 2a) were used in the lower section, followed by tubes in the mid section with outer surface suitable for nucleate-convective boiling and twisted tape inserts inside as shown in Fig. 2b. The top section carried weak nucleate-boiling characteristic tubes (Fig. 2c) in order to minimize the adverse effects of vapor blanketing. For inside enhancement twisted tape turbulators were use. This resulted in a very efficient evaporator that fitted in a designated confined space with low refrigerant charge comparable to the original two shell and plate evaporators. The design parameters and physical characteristics are shown in Table 1. For comparison purposes Table 1 also shows a conventional shell and tube evaporator with plain surface tubes. The chiller has been operational for several years now.

Figure 2a Nucleate boiling characteristic tube in Section I

Figure 2b Nucleate/Convective characteristic tube in Section II

Figure 2c Convective characteristic tube in Section III

Shell and Tube Ammonia Spray Evaporator

Spray evaporators have been successfully used in the winery and poultry industry for decades. This is one other area where enhancement can be applied successfully. One of the positive attributes of spray evaporator is its ability to work under limited charge. This quality can be further augmented by utilizing enhanced tubes. A 3168 kW (900 TR) ammonia

Figure 3 Low-fin carbon steel tube

spray evaporator for cooling water was installed at a chemical plant with double enhanced surface tubes. The top half of the bundle had low fin tubes (Fig. 3) and the lower half carried structured surface tubes as shown in Fig. 4. This concept helped in distributing the cascading liquid ammonia in the lower section of the bundle. For optimum efficiency of spray evaporator it is vital to keep the entire tube bundle wet. Table 2 shows the comparison between this spray evaporator and equivalent capacity conventional flooded evaporator with plain surface tubes. It is obvious that the ammonia charge was orders of magnitude less than a conventional shell and tube flooded chiller.

Shell and Tube Ammonia Direct Expansion (DX) Evaporator

In the past due to immiscibility of mineral oil, DX type evaporators were generally discouraged; however, with the introduction of new synthetic oils miscible with ammonia, such evaporators are being designed. Kelly et al. [4] extensive experimental work with aluminum micro fin tubes over a wide range of saturation temperature, mass flux, heat flux, and inlet quality showed that enhancement could be used in DX evaporators. They found that micro fin tubes showed heat transfer enhancement which was more prominent at the low mass flux where the flow was prone to stratification. The internal geometry helped in wetting the entire tube. The test tubes were thin walled with 12.7 mm (0.5 inch) OD, 60 fins and 17° helix angle.

Figure 4 Structured surface carbon steel tube

Figure 5 Enhanced tube in carbon steel for ammonia DX evaporator

Since ammonia has relatively large latent heat, the mass fluxes encountered in the evaporators are generally lower than an equivalent halocarbon evaporator. In view of this characteristic it is logical to use tubes with larger helix angles.

Table 3 shows comparison between a plain tube versus enhanced tube 215 kW (61 TR) DX evaporator. The enhanced tubes had internal grooves and low profile 750 fin/m (19 fin/inch) on the outside surface. The tube material was carbon steel with 19 mm (0.75 inch) outside diameter and 1.25 mm (0.049 inch) wall thickness under the fin as shown in Fig. 5. A high ridge internal groove with larger helix angle was selected to overcome the low mass flux effect. It is believed that such an internal geometry works well with ammonia due to its higher surface tension which is approximately twice that of R-22 or R-134a.

FURTHER DEVELOPMENTS IN SHELL AND TUBE TECHNOLOGY

There is a need for future research and development on the subject of heat transfer enhancement in ammonia refrigeration systems. In a pending patent application Ayub [5] disclosed a novel design for a flooded shell and tube evaporator as shown in Fig. 6. The interior volume of the shell is filled with multiple diameter filler beads. These beads have neutral buoyancy when immersed in the refrigerant such as ammonia. This minimizes the possibility of beads accumulating at the bottom of the shell (if negative buoyancy) or at the top (if positive buoyancy), hence, assuring the even distribution of the filler beads throughout the shell. The beads could be of different sizes. The largest size bead in the batch has to be small enough to pass through the clearance between any two adjacent tubes in the bundle. The idea behind this concept is to reduce the refrigerant charge in a flooded evaporator. Also the mobility of these beads helps in efficient movement of the bubbles away from the surface and therefore resulting in further enhancing the boiling heat transfer. The filler beads can be put into an evaporator before the evaporator's initial start-up. Alternatively, an existing evaporator can be retrofitted with appropriate beads.

DEVELOPMENTS IN PLATE HEAT EXCHANGER TECHNOLOGY

Plate exchangers are a prime example of heat transfer augmentation devices. Their geometry gives them this characteristic which makes them compact. In the past fifteen years plate type exchangers have made its way in ammonia refrigeration systems. Semi-welded type plate exchangers are commonly used as evaporators in food plants. The plates are similar to a gasket plate except the two adjacent plates are welded together. The welded pair is usually called a plate cassette as shown in Fig. 7. Two opposite-chevron plates are precision laser welded, therefore, eliminating the flow gasket on the refrigerant side. Refrigerant is confined within the cavity created by the welding of two adjacent plates. However, it is important to mention that it is still not a gasket free unit. The ports have to be sealed with ring gaskets in order to avoid refrigerant and process fluid mixing. All-welded plate evaporators are also currently available for ammonia application.

Design information and correlations are either lacking or insufficient in the open literature. Ayub [6] presented a comprehensive literature search on the subject with presentation of new heat transfer and pressure drop correlations for flooded, gravity feed, and DX evaporators. The correlations are based upon a decade of design, field experience and after installation data collected on ammonia and R-22 direct expansion and flooded evaporators installed in North America. It is important to note that in a DX type plate evaporator, appropriate provisions be incorporated to properly distribute ammonia at the inlet port.

It is apparent that nucleate boiling probably plays its role at the lower section of a plate in a flooded system. This aspect could be enhanced by modifying the surface structure of the lower third of the plates in contact with the refrigerant as suggested by Ayub [6]. Longo et al [7] carried an experimental work on a similar concept. They studied evaporation and condensation of R-22 on plates with cross-grooves on the entire plate. Their results showed 30-40% enhancement in vaporization and 60% in condensation compared to smooth surface plates. This idea certainly needs further research and optimization.

The latest on-going ASHRAE studies on ammonia evaporation, 1352-RP [8] and carbon dioxide condensation, 1394-RP [9] in plate heat exchangers will certainly contribute valuable information to the open literature. In research project 1352-RP experiments were conducted on commercial chevron plate heat exchangers with three different geometries. The refrigerant mass flux and heat flux range was 8 – 27 $kg/m^2.s$ and 7 - 42 kW/m^2 for four saturation pressures, respectively. The two phase heat transfer coefficient increased with increasing mass and heat flux and with decreasing saturation

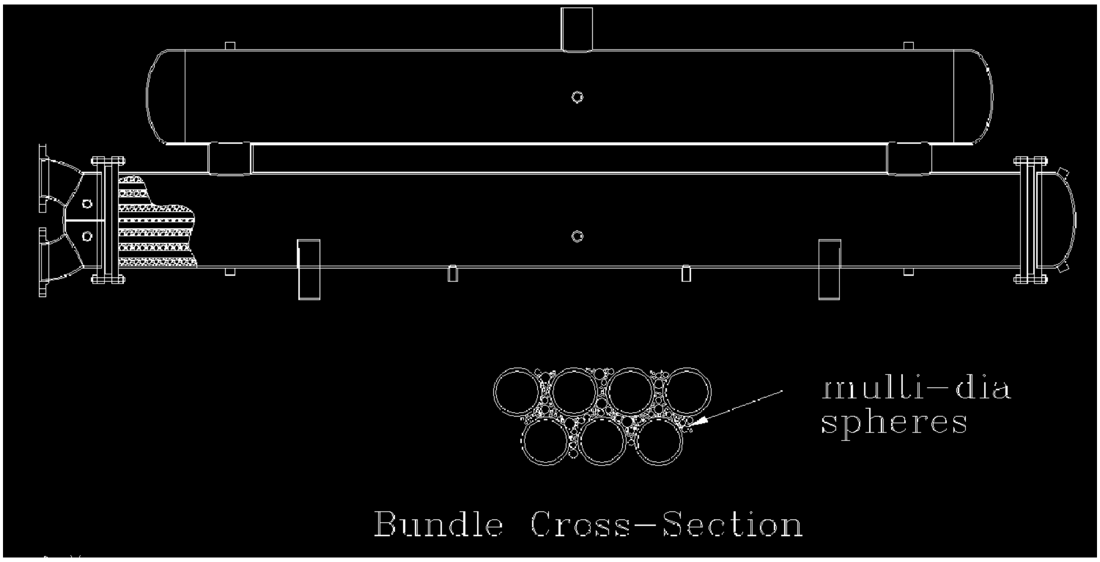

Figure 6 Low charge flooded evaporator with bouyant beads

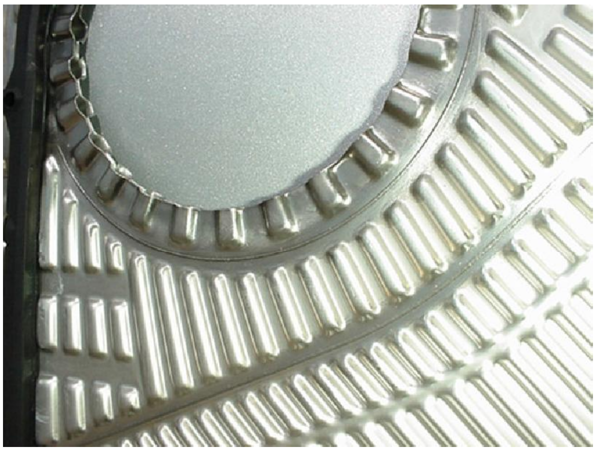

Figure 7 Laser welded cassette

pressure. Both nucleate and convection boiling regimes were observed with nucleate boiling dominating in low heat flux and high system pressures while convective boiling dominated in higher heat flux and low saturation pressures. Pressure drop is found to increase with increasing mass flux and decreasing system pressure. Effect of heat flux was not significant on pressure drop. The two phase friction factor was found to decrease with increasing exit quality, mass and heat flux, while effect of heat flux was moderate at high flux values. The pressure drop, however, increased with increasing saturation pressure.

In the research project 1394-RP [9] three brazed plate heat exchangers with different chevron angle, each consisting of three channels, are being experimentally analyzed in this study. The condensing heat transfer coefficients of the high profile plate were higher at any given flow than the mixed and low profile plates under the same flow conditions. The low profile plate exhibited heat transfer behavior that was more scattered than that of the other two profile plates. This could be attributed to laminar or transitional flow regime, whereas the medium and high profile plates seem to have been most likely in the turbulent regime. The condensation correlations fit the experimental data very well, as presented in Fig. 8.

$$Nu_{tp} = 0.53 Re_l^{0.69} Pr_l^{0.35} \left(\frac{G^2}{\rho_l^2 c_{p,l} \Delta T}\right)^{1.05} \left(\frac{\rho_l^2 i'_{fg}}{G^2}\right)^{0.85} \left(\frac{\rho_l \sigma_l}{\mu_l G}\right)^{0.08} \left(\frac{\rho_l}{\rho_l - \rho_v}\right)^{0.7} \left(\frac{\beta\pi}{180}\right)^{0.06} \tag{1}$$

where β is in degrees. The above correlation was found to have an average standard deviation and uncertainty of less than 10% and 8%, respectively. The results from this study will enhance the literature on the subject and the resulting correlation will help design engineers in the field.

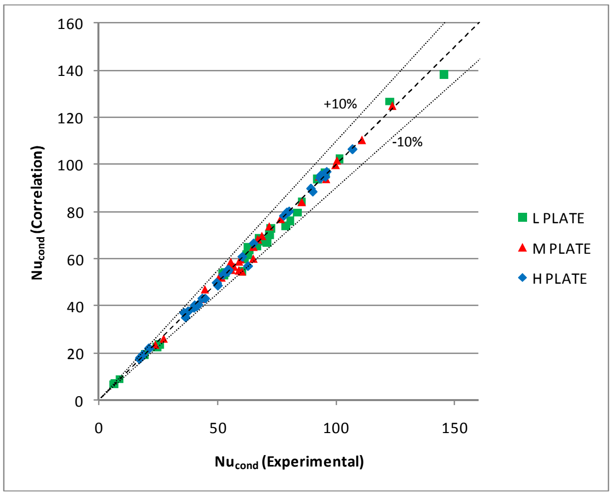

Figure 8 Experimental and correlated Nu for the three CBE

DEVELOPMENTS IN MICRO-CHANNEL TECHNOLOGY

During the last decade extensive research has been conducted in both single phase and two phase areas with primarily aluminium and copper blocks. This technology is being considered for carbon dioxide application especially in the automotive industry. With smaller equivalent diameter these exchangers have the capacity to withstand high working pressures as required by carbon dioxide systems. This same technology can also be extended to hydrocarbons and even ammonia with aluminum as the material of construction. One such conceptual design could be a rectangular exchanger with ammonia boiling on the outside and carbon dioxide condensing on the tube side in ammonia/carbon dioxide cascade system.

The use of mini and micro channel exchangers can also be explored for use as evaporators and condensers in ammonia systems. Since copper is not compatible with ammonia and steel is harder to work with, aluminum extruded exchangers could be used. However, as noted earlier the internal fin geometry and fin helix angle has to be optimized for ammonia. Most of the work in this area relates to halocarbons and because of ammonia's different transport properties the geometry implication is crucial. Vollrath et al. [10] performed a detailed experimental test on straight fin aluminum micro fin tubes with ammonia condensation and apparently found no improvement in heat transfer. Some improvement was achieved after filing the fin tips. It is not clear whether the improvement was a result of lower fin profile or actual physical change introduced in the fin tips due to the filing operation.

CONCLUSION

The paper presents the status of ammonia and other natural refrigerants as viable refrigerants with wider role to play in the future. The traditional technology is compared with the emerging enhancement technology in ammonia systems. Some of the recent experiences with enhanced heat transfer surface exchangers in ammonia applications are summarized. The paper also presents the use of plate exchangers in ammonia and carbon dioxide systems and the lack of good engineering data and design correlations.

There are still unknowns that need to be explored by researchers. There is a need for reliable correlation for in-tube boiling with pure ammonia and ammonia/oil mixtures in enhanced tubes. Therefore, specific geometry enhanced tubes have to be initially produced by the tube manufacturers. The paper indicates that present geometries designed for halocarbons are not optimized for ammonia applications. New alloys that are less expensive, easily machined and compatible with ammonia and/or ammonia/oil mixture have to be developed. Further research is required in the area of DX and spray evaporation with hydrocarbons especially propane and isobutane.

New technologies at the nano scale level have to be explored for future natural refrigerant systems.

Table 1
Multiple type enhanced tube evaporator vs. plain tube flooded evaporator

Characteristics	**Existing**	**Plain tube flooded**
Shell OD, mm (in)	1067 (42)	1676 (66)
Tube length, mm (in)	2972 (117)	7315 (288)
Tube OD, mm (in)	19 (0.75)	19 (0.75)
No of tubes	1400	4000
No of passes	3	8
Pressure drop, bar (psi)	1.2 (17.5)	1.4 (19.4)
Price $ (year 2004)	48,000	165,000
Ammonia charge, g/KW (lbs/TR)	482 (3.74)	2840 (22)

Design capacity:	1760 kW (500 TR)
Refrigerant:	Ammonia at -5.56°C (+22°F) saturated suction temperature
Process fluid:	40% wt/wt propylene glycol
Process flow:	421 m^3/hr (1854 gpm)
Process inlet:	+1.67°C (+35°F)
Process outlet:	-2.22°C (+28°F)

Table 2
Comparison of spray evaporator with a same capacity flooded evaporator

Characteristics	**Existing Spray Unit**	**Conventional Flooded Unit**
Shell diameter, mm (in)	1219 (48)	1524 (60)
Tube length, mm (ft)	5182 (17)	7315 (24)
Tube outside diameter, mm (in)	19 (0.75)	32 (1.25)
No of passes	2	8
Pressure drop, bar (psi)	0.52 (7.5)	0.76 (11)
Ammonia charge, g/kW (lb/TR)	64 (0.5)	1290 (10)

Table 3
Existing enhanced tube DX evaporator vs. plain tube DX evaporator

Characteristics	**Enhanced tube (existing)**	**Plain tube**
Shell diameter, mm (in)	300 (12)	400 (16)
Tube length, mm (ft)	228 (9)	254 (10)
Tube OD, mm (in)	19 (0.75)	19 (0.75)
No of passes	4	6
Brine pressure drop, bar (psi)	0.57 (8.2)	0.58 (8.4)
Price $ (year 2004)	6,933	9,560
Ammonia charge, g/kW (lbs/TR)	30 (0.23)	62 (0.48)

Design capacity:	215 kW (61TR)
Ammonia sat. temp:	-24°C (+5°F)
Process fluid:	23% wt/wt Calcium Chloride
Process flow:	78 m^3/hr (343 gpm)
Process inlet:	-6.7°C (+20°F)
Process outlet:	-9.4°C (+15°F)

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