INNOVATIVE COMPONENTS FOR ADVANCED SYSTEMS

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ABSTRACT

Continuing efficiency improvements in air conditioning and refrigeration systems will require continued improvements in component technologies. Such improvements are necessary, but they are not sufficient. This paper explores the relationships between component and system efficiencies, and the ways in which demand for improved system performance is driving innovation in the component industries. The emerging trend towards integrated systems is addressed explicitly.

Key words: ***vapor compression systems, refrigeration, air conditioning, integrated systems***

1 INTRODUCTION

Recent research has led to substantial improvement in the performance of individual components in refrigeration systems. For small (<10 kW) systems, much of this new technology development has been driven by implementation of appliance energy efficiency standards in North America and Japan, by very high electricity prices in some parts of Asia and rapid growth in heat pump demand in other parts where the electricity distribution infrastructure cannot handle many inefficient systems. In other words, component efficiency improvements are driven mainly by market- or policy-based demands for improving overall system efficiency. In many parts of the HVAC industry this shift in focus is a departure from its historical evolution as a commodity industry dominated by intense pressures to focus innovation on cost reduction while holding other attributes constant, except those critical to product differentiation.

This paper is therefore structured as a walk through the process of designing a heat pump *system*, discussing component innovations in terms of their contributions to overall system performance. It proceeds in three stages, considering the task of developing components to increase efficiency for:

1. A simple, 4-component vapor compression cycle at single design point;
2. The same system at off-design conditions;
3. Adding components to bring the thermodynamic cycle closer to Carnot ideal; and
4. Integrating the heat pump with the larger systems that it serves.

Only five basic components are required – theoretically – for a system to operate the ideal vapor-compression cycle (two heat exchangers, compressor, expansion device, and refrigerant). The following subsections describe improvements in system efficiency that are now being achieved through improved design and control of these basic components. The next section describes how additional improvements in system efficiency are being realized through the addition of other components that modify the thermodynamic cycle, bringing it closer to the Carnot ideal; e.g. receiver, separator, internal heat exchanger, expander or multistage compressor. The final section addresses system integration issues that offer further opportunities for satisfying customer demands by optimizing within a larger system boundary; e.g. secondary loops and integrated load management.

2 IMPROVING THE BASIC COMPONENTS

To operate on the basic vapor compression cycle at a particular design point, only passive components are required. To approach the ideal vapor compression cycle at off-design conditions would require compressor and air flow modulation and some form of charge management. Only the flow modulation issues are discussed in this section; charge management is deferred to the following section because it requires an additional component.

The discussion begins by focusing on the standard vapor compression cycle, with the system operating at a single design condition. The thermodynamic cycle alone defines the efficiency of this idealized cycle where the evaporator and condenser outlet states are saturated vapor and liquid, respectively, and the refrigerant flow rate determines the system capacity. That, in turn, is determined by the compressor displacement rate as discussed below.

2.1 Condenser and Evaporator

The standard cycle cannot match the ideal cycle efficiency because the heat source and sink are finite and require energy for pumps or blowers. The ideal heat evaporator or condenser would have infinite face area and infinitesimal thickness in order to minimize the power required to move an infinite amount of air or other fluid over the heat exchanger. Today's most efficient heat exchangers, therefore, employ heat transfer enhancement techniques on both the refrigerant and air sides to minimize heat transfer resistance subject to a face area constraint. The temperature difference in an evaporator or condenser is limited by the pinch condition at the trailing edge of the fin. Therefore the optimal heat exchanger depth occurs at a point where the compressor power saved by increasing/decreasing the evaporating/condensing temperature is exactly offset by the fan power increase needed to increase the thermal capacity of the heat source or sink.

When the source/sink is a liquid, the heat transfer resistances on the liquid and refrigerant sides are roughly the same order of magnitude. One of the most remarkable advances in this technology occurred decades ago with the introduction of brazed plate heat exchangers originally developed for liquid-liquid applications. Surface patterns on the plates (e.g. wavy chevrons) create a chaotic laminar flow in many parallel (and communicating) channels between the braze joints, resulting in large-scale vorticity that produces single-phase heat transfer coefficients that can be significantly larger than those in two-phase flow on the opposite side of the many parallel plates (Muley and Manglik, 1999; Bogaert and Bölcs, 1995).

When heat is transferred between two-phase refrigerant and air the heat transfer resistance on the air side is often 90% or more. Therefore to minimize material cost (and air side pressure drop) recent technology development has focused on enhancing air-side performance by exploiting three basic phenomena. The first is to re-start the boundary layer through use of louvers and offset strips, or wavy channels to cause the boundary layer to separate and re-attach (DeJong et al. 1998). The second is to exploit the periodic shedding of spanwise vorticity (von Karman vortex street) that occurs in the downstream portion of a louver array – it produces enough of an angle of attack on the next louver to cause a tiny vortex to shed from its leading edge and travel to the trailing edge, thinning the thermal boundary layer as it goes. The third approach is to use vortex generators (e.g. hemispherical bumps or winglets) to create streamwise vorticity similar to that generated at aircraft wingtips; the vorticity brings fresh air into the boundary layer (Gentry and Jacobi, 1997; Jacobi and Shah, 1995).

In air conditioning applications, removal of moisture in the form of liquid condensate is a benefit, while in refrigeration and space heating it is totally parasitic. Condensate and frost can nullify heat transfer enhancements by closing gaps in interrupted surfaces, and increasing air side pressure drop. Therefore the most recent innovations in fin design are aimed at minimizing the amount of condensate retained on the surface and preventing bridging between louvers and between fins (Korte and Jacobi, 2001). Various approaches are being considered, including hydrophilic and hydrophobic surface treatments. To minimize the adverse effects of frosting, multi-module heat exchangers are being designed to allow more flexibility for fin staging and distributing frost in such a way that a near-uniform free flow area is maintained from the upstream to downstream end of the evaporator (Chandrasekharan and Bullard, 2005). In refrigerators and heat pumps, frost deposition can be minimized by increasing overall UA, a strategy that is consistent with maximizing system efficiency in any event.

The most commonly employed method for enhancing refrigerant-side heat transfer is to build extended surfaces inside the tubes. These take the form of microfins in round tubes that can increase surface area by approximately 60%; spiral configurations are used to wet the top of evaporator tubes when mass flux is low. Another approach is to increase the surface area carrying a given mass flux, by using flat tubes of rectangular cross section, with multiple ports formed by webs that provide structural integrity equal to or greater than that of an equivalent circular tube. Such flat “microchannel” tubes also provide more contact area with the fins, and enable fin designs with slits or louvers running parallel to the heat flux instead of interfering with it as in the case of round tube-plate fin heat exchangers.

In a/c evaporators the design criterion for dehumidification sets an upper limit on fin surface temperature (~14°C). For an efficient system this limit becomes the design target, thus defining the minimum required air flow rate. With packaging constraints limiting the evaporator’s face area, the tradeoff between fin pitch and heat exchanger depth is optimized to minimize the fan power. Since evaporator fin temperature is a design target, the role of air-side heat transfer enhancement is to reduce the required surface area, not to increase evaporating temperature. R&D to reduce overall log mean temperature difference in non-frosting evaporators therefore focuses on refrigerant-side enhancements. However in refrigeration where frost is an issue, air side enhancements have greater payoff because the warmer surfaces minimize the parasitic effects of frosting.

2.2 Compressor

With the standard vapor compression cycle defining the saturated suction inlet condition, and the heat exchanger designs defining the suction and discharge pressures, the task of the compressor designer is to maximize isentropic efficiency by minimizing frictional losses and internal heat transfers. The displacement rate is dictated by the system capacity requirement at the design condition; it can be minimized by increasing the volumetric efficiency.

Compressor efficiencies increased rather rapidly during the last two decades, primarily by eliminating excessive heating of the suction gas (recall that $dw = v*dp$). This was accomplished by increasing motor efficiency, using rotary compressors with high-side oil sump, and rejecting more heat through the compressor shell instead of relying on cold suction gas to cool the motor.

2.3 Expansion Device

Variable expansion devices such as thermostatic and electronic expansion valves are controlled with the goal of maximizing evaporator capacity at all operating conditions by maintaining the outlet as near as possible to the saturated vapor state; i.e. the ideal vapor compression cycle. Fixed short-tube orifices and capillary tubes are a less costly alternative, but such passive devices sized for a particular design condition generally fall short of that goal at off-design conditions.

2.4 Refrigerant

The refrigerant charge is a key component of any system. If the expansion device is seen as controlling the evaporator outlet, the charge determines the condenser outlet state. Together the amount of charge and the expansion device opening enable the system to meet the target evaporator and condenser exit states in critically-charged systems at the design condition.

A refrigerant's thermodynamic properties determine its ideal-cycle efficiency, but transport properties such as conductivity, and viscosity can sometimes offset a thermodynamic advantage and reduce overall system efficiency. While differences in transport properties can sometimes be accommodated by component design (e.g. changing tube diameter), additional components (e.g. multistage compressor, internal heat exchanger) are often needed to offset shortfalls in ideal cycle efficiency.

3 MAXIMIZING SYSTEM PERFORMANCE AT OFF-DESIGN CONDITIONS

After selecting components to approach – as closely as possible – the ideal vapor compression cycle at a particular design condition, the next step towards improved efficiency it to modulate refrigerant and air flow rates to maintain near-ideal system performance at off-design conditions. The development of efficient variable-speed drives is accelerating this trend.

Modulating compressor displacement rate is the key, because it allows the system to run continuously, utilizing the available heat transfer surface 100% of the time. Whenever the heat duty is greater or less than the design load, variable-speed fans modulate both the magnitude of the heat source/sink and the air-side heat transfer resistance. Their speed at any operating condition can therefore be selected to maximize system efficiency, or some other constrained tradeoff among other objectives such as low noise or dehumidification.

The simplest way to think about efficient off-design performance of an a/c system, therefore, is to set the compressor speed to maintain indoor dry bulb temperature, and the evaporator fan/blower speed to maintain the desired humidity, while adjusting the outdoor fan speed to minimize the sum of compressor and fan power at any operating condition (Andrade and Bullard, 2002). The expansion valve in such a system would play the same role as it has in the past – ensuring that the two-phase zone of the evaporator is as large as possible. Note that in many refrigeration applications the desired humidity is quite high, so the optimal evaporator fan speed is likewise high.

The benefits of flow modulation technologies are therefore not limited to the energy efficiency improvement associated with the lower temperature lift. Conventional systems with single-speed drives cycle on/off to meet sensible loads and cannot simultaneously match latent loads. Therefore they waste energy removing too much water at some conditions and fail to meet comfort criteria at others. Moreover their tradeoff between air-side heat transfer and pressure drop are optimal only at the design condition, and not at others. In single speed systems the user has no option to trade efficiency for comfort or for quieter operation at extreme conditions.

4 ADDING COMPONENTS TO THE BASIC CYCLE

Additional components are installed in vapor compression systems for two fundamental reasons: 1) to make the basic cycle and its components work better; or 2) to bring the shape of the thermodynamic cycle closer to the Carnot ideal.

4.1 Improving Basic Cycle Efficiency

Many automotive a/c systems are equipped with short-tube orifices, despite their potential inefficiency, because the systems are not operated during the test that measures vehicle fuel economy. The optimal designs tend to be ultra-compact to save space and weight, used fixed orifices for reasons of cost and reliability, and added a low-side receiver at the evaporator exit to protect the compressor across the extremely broad range of operating conditions encountered in automotive applications (compressor speeds were uncontrolled). At all steady state conditions, the receiver maintained the evaporator outlet at the saturated vapor state while at the same time providing extra refrigerant storage as insurance against inevitable leakage through the flexible hoses and the open compressor shaft seal.

4.1.1 Receivers

Thus the combination of a simple fixed expansion device and a low pressure receiver can be viewed as a low-cost completely passive alternative to a TXV or EXV. Both protect the compressor, and control the evaporator exit state. They are common on window a/c units and reversible heat pumps.

High-side receivers are often used in conjunction with expansion valves in systems where high energy efficiency is required. In such cases the expansion valve controls the evaporator outlet while the receiver maintains a saturated liquid condition at the condenser outlet over the full range of steady state operating conditions. These components were added first to improve efficiency in supermarket refrigeration and auto a/c applications where refrigerant storage was also needed to compensate for high rates of refrigerant leakage. To prevent flashing of the saturated vapor as it flows through a long liquid line, such systems are often equipped with a small subcooler downstream of the receiver. In mass-produced systems the subcooler, condenser, and receiver are often integrated into a single component.

High-side receivers of course could be used to improve the efficiency of any system that experiences excessive subcooling over part of its operating range, by allowing it to operate at a lower condensing temperature. However in a leakproof critically-charged system, it is often possible to avoid conditions of excessive subcooling through careful design of the evaporator and condenser, so the sum of their respective charge requirements are nearly constant across the operating range. This is clearly a potentially less costly solution if it can be accomplished without a significant loss of heat exchanger effectiveness.

4.2 Altering the Thermodynamic Cycle

The ideal reversed-Rankine vapor compression cycle departs from the Carnot ideal in two ways. Most of the dissipation occurs in the isenthalpic expansion, while a lesser amount is attributable to heat transfer across a finite temperature gradient while desuperheating the suction gas.

4.2.1 Internal heat exchangers

Internal (liquid-to-suction) heat exchangers are added to some systems for two basic reasons: 1) to increase cycle efficiency; or 2) to protect the compressor from liquid slugging. They are used on all domestic refrigerators, because the thermodynamic properties of both R-12 and R-134a enable a 5-10% improvement in cycle efficiency because the increase in specific work due to the superheating of suction gas is substantially less than the increase in refrigerating effect caused by the additional subcooling (Domanski et al. 1994). Similar benefits are obtainable in the transcritical R744 cycle under the high-lift conditions experienced in automotive a/c applications (Boewe et al. 2001). In second law terms, the efficiency increase is attributable mainly to reducing irreversibility at the expansion device by allowing the refrigerant to enter the evaporator at a lower quality. Many modern supermarket display cases are being equipped with internal heat exchangers to improve efficiency whenever the refrigerant properties produce a net benefit (e.g. R404A).

The thermodynamic properties of other refrigerants (e.g. R410A), produce no net increase in COP when the cycle is changed by adding an internal heat exchanger, and in some cases (e.g. R22) simple thermodynamics dictates a net loss of 5% or more, depending on the operating conditions. However for refrigerants (or low-lift operating conditions) where the effects on efficiency are small, the addition of an internal heat exchanger can still protect the compressor from liquid slugging – for example at startup and during other transients.

In domestic refrigerators the mass flow rates are so low that the capillary tube must be 2 to 3 m long in order to have a diameter large enough (>0.7 mm) to prevent clogging. Refrigerant enters first enters an adiabatic section of the capillary tube, usually in a subcooled state, flashes and then and proceeds to a ~1 m diabatic section where it transfers heat to the suction line. The remaining pressure loss occurs in a shorter adiabatic outlet section. In the past when the physics of the diabatic flow was poorly understood and could not be modeled, the tedious experimentally-based empirical design process focused mainly on the task of protecting the compressor and the energy efficiency benefits were merely incidental. Recent research has revealed the complexity of the flow regimes (e.g. recondensation occurring in the diabatic portion and re-flashing in the outlet section, and the potential for losing the choked outlet state under some conditions), and enabled simulation-based designs to not only improve cycle efficiency but also shorten the costly process of testing candidate configurations emerging from the multidimensional optimization process (varying captube diameter, adiabatic inlet and outlet lengths). See Jain and Bullard (2004).

In supermarket display cases and transcritical R744 systems, recent research has led to designs of ultra-compact and highly effective internal heat exchangers consisting of a 3-layer "sandwich" of flat multiport tubes.

4.2.2 Expanders

While subcooling (naturally, mechanically, or via an internal heat exchanger) upstream of a throttling device can reduce the thermodynamic irreversibility of an isenthalpic expansion process, an isentropic expander can theoretically eliminate it, recovering the work by expanding through a turbine or other (positive displacement) device. The economic feasibility of this additional component is limited by several factors, mostly scale-related. Research has therefore been focused on refrigerants and applications where irreversibilities are inherently large, i.e. where high lift and/or shallow-sloped vapor pressure curve leads to high evaporator inlet quality after isenthalpic expansion.

To be cost-effective, a substantial fraction of the ideal work must be recovered, after accounting for conversion (e.g. to electricity) and transmission (e.g. mechanical) losses, and for the mismatch between work produced and work needed (e.g. in the case where it might be used to power an evaporator fan to avoid conversion and transmission losses). For these reasons recent turbine-related research is focusing on where their edge losses can be minimized by using a low-pressure refrigerant in large-scale applications (e.g. R134a chillers; see Brasz, 19). Other schemes under investigation seek to employ positive-displacement devices and the option of transmitting the work directly to run the second stage of a multistage compressor.

Since expanders and internal heat exchangers compete to reduce the same source of irreversibility in the vapor compression cycle, they are unlikely to be used together except in special circumstances now being defined by recent thermodynamic analyses. Overall, however, expanders offer the theoretical possibility of completely eliminating expansion losses, while internal heat exchange has unavoidable losses due to poor matching of temperature glides and the lowering of suction gas density.

4.2.3 Ejectors

An ejector is a potentially isentropic device designed to use the pressure gradient and kinetic energy of the expansion process to increase the pressure of the suction gas entering the compressor. It receives high pressure liquid from the condenser, expands it to the evaporator pressure to entrain the vapor, then diffuses the resulting two-phase mixture to an intermediate pressure where a separator sends the liquid through a insenthalpic expansion into the evaporator while sending the intermediate-pressure saturated vapor to the compressor. Interest in this approach has been revived recently to capture the relatively large amount of energy recoverable in transcritical R744 systems (Elbl and Hrnjak, 2004).

4.2.4 Multi-stage compressors, intercoolers, and separators

For many years these additional components have been included in large custom-built industrial refrigeration systems to increase system efficiency, but have not been employed in small mass-produced systems because of the cost-reduction focus that dominates a commodity industry. However recent research is revisiting the issue as modern manufacturing technologies make these components a potentially economical way to respond to demands for more efficient systems.

Multi-stage compression reduces even the ideal work required to compress the suction gas by intercooling after each stage to reduce the specific volume of the vapor by desuperheating, sometimes sending saturated vapor to the next stage. If the heat is rejected to the external environment, the principal source of efficiency improvement is the reduction of vapor volume. On the other hand the heat can be rejected internally via condensation in a separator operating at some intermediate pressure along a multi-stage expansion process. The separator supplies the next expansion device with saturated liquid (producing a very low-quality evaporator inlet to aid flow distribution flow distribution) while sending low-volume saturated vapor to the next compressor stage. Viewed differently, only part of the vapor needs to be compressed through the entire pressure lift; the remainder need only be compressed from some intermediate pressure before re-entering the condenser. The separator in this case may need a float valve in order to maintain a steady flow condition.

Another way to achieve the same thermodynamic cycle improvement is to evaporate a small amount of liquid at an intermediate pressure to subcool the high-pressure liquid leaving the condenser, instead of using a separator. However that option too requires an additional valve.

In recent years the increasing use of screw and scroll compressors has created opportunities to capture the benefits of multistage compression by injecting intermediate-pressure vapor (from separators or subcoolers) into multiple locations along the screw or scroll pockets (Jain et al. 2004). Other innovations include the use of multiple inlets to adjust the volume ratio of a single scroll compressor.

Finally separators are being used to separate vapor after a complete one-stage expansion process in order to feed the evaporator with saturated liquid while bypassing all the vapor to the suction line. While this does not improve thermodynamic cycle efficiency, it does enable refrigerant to be distributed uniformly among many parallel circuits in the evaporator, eliminating one of the most serious impediments to implementation of microchannel evaporators, for example (Elbl and Hrnjak, 2004).

4.2.5 Secondary loops

The refrigerants of the future will be more costly, flammable, or hazardous than those of the past. Therefore research and technology development activities are exploring ways to minimize refrigerant charge, even in refrigerant-to-air heat exchangers. Greater reductions can be achieved by transferring heat to a secondary fluid (e.g. a single-phase brine or possibly 2-phase bubble-pumping operation) in an ultra-compact evaporator and condenser. The secondary loop entails two energy penalties: pumping power in the secondary loop and an additional temperature difference at the evaporator and condenser. However these penalties can be partially offset by other benefits. For example in supermarkets frost can be deposited more evenly by managing the temperature glide of the secondary refrigerant to the air, shorter suction lines mean higher suction pressures, the superheated zone can be eliminated from the display case coil, and developing flow effects can be exploited in the secondary refrigerant to bring the secondary fluid's heat transfer coefficient nearer to that of a two-phase fluid (Elovitz et al. 2001).

5 INTEGRATING HEAT PUMPS WITH THE LARGER SYSTEM

In the interest of decreasing cost and/or increasing efficiency, it may someday become economically feasible to build even more complex systems that provide more than heating or cooling. For example a reversible heat pump system provides both. A slightly more complex system may also provide domestic water heating while sharing many of the same components with the heat pump used for space conditioning.

In large buildings the heating and cooling system is already integrated with the ventilation system, and this trend may spread to smaller buildings as rising energy prices make it feasible to recover both sensible and latent heat from ventilation air instead of relying on infiltration to bring in fresh air. Already there are many demonstration projects, primarily in Europe, where conduction and infiltration loads have been reduced to a point where space heating loads can met by heating the ventilation air alone. The high temperature of heat rejection in the transcritical R744 systems is especially compatible with this approach, and is most efficient when the heat is pumped from a geothermal source.

Similar opportunities arise when one envisions fundamental reductions in the magnitude of cooling loads through improved building insulation, reduction of infiltration, ventilators that recover sensible and latent heat, and electrochromic or photochromic glass to minimize solar gain. The air conditioning system required to meet such small loads may require components that are radically different from those built today. For example in some climates it may be sufficient to meet a substantial portion sensible cooling load as a byproduct of the domestic water heating process, extracting heat from either the ventilation air or from radiant panels operating above the dewpoint of the indoor air. Latent loads, having been minimized by tight construction and an enthalpy-recovery ventilator, might be met separately with liquid dessicant in the building's air purifier.

Another level of system integration might be envisioned in a future where energy costs are much higher than today and building construction trends continue. Already many types of buildings are assembled on-site from integrated components made in factories, for example insulated wall panels (with windows) that may also be structural members. Considering that a building's thermal loads are transmitted through such wall panels, it may be possible for the inner and outer surfaces to serve as the evaporator and condenser for an embedded heat pump system, relying only on natural convection and radiation because of the relatively low heat fluxes involved. It is even conceivable that such heat pumps could be integrated with photovoltaic cells on the outdoor surface, capturing much of the radiant energy not converted to power during winter.

All these scenarios have tremendous implications for the design of components for a vapor compression heat pump. The lesson to be drawn from such brainstorming is not that any such scenario may in fact materialize. Rather, it illustrates how component designs are dictated by larger system performance criteria. And the larger system may be required to deliver shelter, silence and electricity as well as thermal comfort, hot water and cold food.

6 CONCLUDING REMARKS

In closing it is worth remembering that this discussion has been limited to the vapor compression cycle, and mostly to equipment that has evolved to meet the large thermal loads associated with inefficiently-designed buildings, vehicles, display cases, and cargo containers. As energy prices rise to reflect the costs of reducing greenhouse gas emissions by 60-70%, we will need heat pumps that are optimized for handling smaller loads. And it is entirely possible that such heat pumping will be accomplished by using different thermodynamic cycles.

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