Waking the Sleeping Giant: Introducing New Heat Exchanger Technology into the Residential Air-Conditioning Marketplace

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ABSTRACT

The Air Conditioning Industry has made tremendous strides in improvements to the energy efficiency and reliability of its product offerings over the past 40 years. These improvement can be attributed to enhancements of components, optimization of the energy cycle, and modernized and refined manufacturing techniques.

During this same period, energy consumption for space cooling has grown significantly. In January of 1992, the minimum efficiency requirement for central air conditioning equipment was raised to 10 SEER. This efficiency level is likely to increase further under the auspices of the National Appliance Energy Conservation Act (NAECA). A new type of heat exchanger was developed for air conditioning equipment by Modine Manufacturing Company in the early 1990's. Despite significant advantages in terms of energy efficiency, dehumidification, durability, and refrigerant charge there has been little interest expressed by the air conditioning industry. A cooperative effort between Modine, various utilities, and several state energy offices has been organized to test and demonstrate the viability of this heat exchanger design throughout the nation. This paper will review the fundamentals of heat exchanger design and document this simple, yet novel technology. Test experiences involving equipment retrofits have been documented with respect to the performance potential of air conditioning systems constructed with PF™ Heat Exchangers (generically referred to as microchannel heat exchangers) from both an energy efficiency as well as a comfort perspective. The paper will also detail the current plan to introduce 16 to 24 systems into an extended field test throughout the U.S which commenced in the Fall of 1997.

Background

How Does a Heat Exchanger Work ?

In any kind of space conditioning (heating or cooling) application, the primary objective of the process is to change the temperature of the conditioned space and, in the case of cooling, to lower the relative humidity. There are numerous ways in which this can be accomplished:

- air passing over cold water tubes : chilled water system
- air passing over tubes containing cold refrigerant : typical air conditioning system
- air passing over hot water tubes :hydronic heating system
- air passing over tubes containing hot refrigerant : heat pump system
- air passing over "shells" within which fuel is combusted : warm air furnace system

In almost all cases, however, the main transfer agent for this process is a heat exchanger. While there are numerous categories of heat exchangers, space conditioning typically involves a process referred to as indirect contact heat transfer. Indirect heat transfer requires the use of a heat exchanger in which the two fluids (e.g. air, combustion products, water, or refrigerant) are separated from each other by some sort of surface (usually a metal tube surface or plate). Heat always flows from a hot region to a colder region in this process.

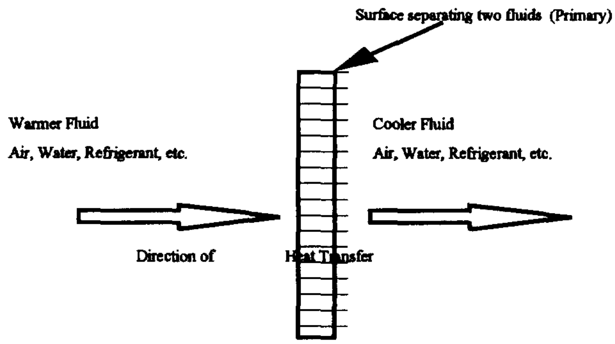


Figure 1.

The larger the difference in temperature between the warm and cold fluids, the larger the driving force for heat transfer and (with all else being equal) the larger the quantity of heat transferred. Unfortunately, in virtually all thermodynamic cycles and the associated heat transfer processes used in space conditioning, there is an ever-increasing energy penalty to be paid as this temperature difference increases. Therefore, from an efficiency perspective, it is a fundamental objective to transfer as much heat with as small of a temperature difference as possible.

While there are many factors which influence the efficiency (usually termed effectiveness) of this process, the essence of the process can be reduced to a small number of factors:

- the ability of the warm fluid to transfer its heat to the intermediate surface
- the ability of the intermediate surface to transfer heat across it to the colder fluid
- the ability of the colder fluid to extract the heat from the intermediate surface

In general, the faster the fluids are moving, the greater the potential to move heat to or from the intermediate surface. Once again however, it is an unfortunate law of nature that usually places an energy penalty on the means by which this fluid velocity is increased (fans, pumps, etc.). Therefore, the choice of fluids by which heat is transferred is extremely important. It is also unfortunate that the very fluid we are usually trying to change the temperature of, air, is a relatively poor heat transfer medium. Almost as important as the fluid, is the type and amount of intermediate surface which is used to conduct heat between fluids. The more surface placed between the hot and cold fluids along with the propensity of the surface to transfer heat (the ***thermal conductivity***), the greater the amount of heat transfer and, usually, the smaller the temperature gradient required to transfer this heat. Figure 1 illustrates the most fundamental of heat transfer processes in which heat is transferred indirectly from one fluid to the next through an intermediate surface. This intermediate surface is called ***primary surface*** because it makes contact with both fluids.

The ability to increase heat transfer can be enhanced by adding a conductive surface to each side of the primary surface as shown in Figure 2.

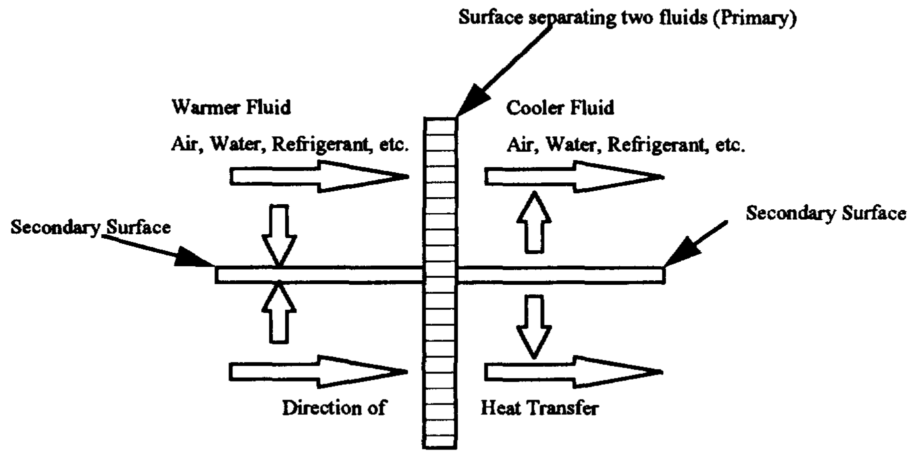


Figure 2.

This additional surface, known as ***secondary surface***, does not make contact with both fluids. Instead, the secondary surface must first conduct heat from one of the fluids to the primary surface. Once the heat has moved into the primary surface it is then conducted into the second fluid either directly from the primary surface or indirectly via a secondary surface in the second fluid stream. There is a resistance to heat movement at the point where the primary and secondary surface come into contact known as ***contact resistance***. In order for any secondary surface to be useful, it must not only possess good thermal conductivity but must also make intimate contact with the primary surface in order to minimize this contact resistance. As heat moves from the hottest point in the fluid stream through the surface, the temperature in that surface decreases as a result of the inherent resistance to heat flow. This decrease in temperature takes the form of a ***thermal gradient***. This is an extremely important concept in heat transfer especially when secondary surface is employed as an agent for effecting heat transfer. The steeper the thermal gradient (and, thus the greater the temperature drop through that surface), the less effective the secondary surface will be. From a material and surface geometry perspective, the effectiveness of the secondary surface is a function of:

- the length of the path that the heat must flow down
- the thermal conductivity of the material from which the secondary surface is composed
- the means by which the secondary surface is attached to the primary surface
- the thickness of the secondary surface or fin

How Do We Improve the Performance of a Heat Exchanger?

From the preceding discussion it can be seen that there are a number of fundamental ways in which the performance of a heat exchanger can be improved:

- Use as much primary surface as possible (to minimize the thermal gradient)
- Heat transfer surfaces should be constructed of materials with good thermal conductivity
- If secondary surface is used, fins should be short and thick (to minimize the thermal gradient) and bonded tightly to the primary surface (to minimize the contact resistance).

One additional point is highly relevant to any discussion concerning space cooling applications. In many, if not most, geographic regions of the world, dehumidification of the conditioned air is as important, if not more important, than the objective of lowering the temperature. The temperature displayed on a typical thermometer is a measurement of what is called *dry bulb temperature*. When air is cooled without dehumidification, the process is called *sensible cooling*. A second measurement which is not normally a control point in air conditioning measures a value referred to as the *wet bulb temperature*. The process by which air is dehumidified is called *latent cooling*. While the HVAC industry recognizes the need for dehumidification, the primary driver in the cooling process has been sensible cooling. In most areas of the country, however, comfort is far more a function of how much dehumidification has been performed rather than by how much the temperature has been lowered. Dehumidification is typically achieved by forcing the relatively damp air to come in contact with a heat transfer surface (tubes, fins) which has a temperature below the *dew point* of the air to be cooled. Primary surface and secondary surface can be an excellent means by which this can be accomplished. However, while both surfaces have inherent thermal gradients, the thermal gradient in the secondary surface often leaves much of that surface above the dewpoint of the air. Any region of this secondary surface with a temperature higher than the dew point of the air passing over it will be incapable of providing dehumidification.

Introduction to Microchannel Heat Exchangers

Most heat exchangers used in air conditioning applications today utilize a design often referred to as round tube plate fin (RTPF). This design as described in Figure 3 has provided a reliable means of heat transfer for these applications for many years.

Cross-section of a Round Tube Plate Fin Heat Exchanger

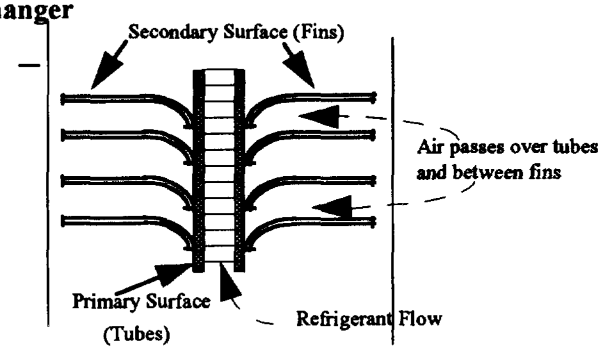
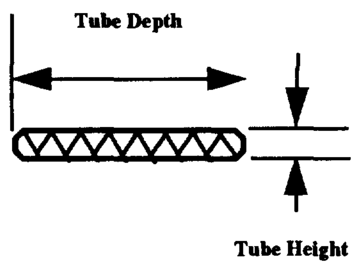


Figure 3.

In a typical air conditioning application, cold refrigerant (in the case of an evaporator) passes through the interior of the tube whereas the air to be cooled passes through the fins and over the outside of the tubes. If the heat exchanger is rejecting heat (the condenser) heat flows from the hot refrigerant in the tube into the "cool" outside air stream. If the heat exchanger is absorbing heat (the evaporator) heat is flowing from the warm air into the fins, the tube wall and, finally, into the cool refrigerant stream. The dashed lines in Figure 3 represent the locations in the fins where the thermal gradients begin and, thus, a point across which heat does not flow. This boundary is called the *adiabatic boundary*. It is either the hottest point on the fin in the case of an evaporator or the coldest point on the fin in the case of a condenser. The typical means of construction for a round tube plate fin heat exchanger utilizes a copper tube (the primary surface) and aluminum plate fins (the secondary surface). Copper and aluminum are both excellent conductors of heat. The means of attaching these fins to the tube, however, is by mechanical expansion. A rod or ball is forced through the copper tube pushing its outer walls outward and into the hole in the aluminum fin. Contact between the two surfaces is, therefore, simply by means of an interference fit between the two surfaces.

The microchannel heat exchanger was invented by Modine researchers during the mid 1980's. At the time, the objective of this development effort was to improve on the fundamentals of heat exchanger performance by reducing the cavity size of refrigerant flow passages, improving the brazing techniques traditionally used in radiator construction, improving the ability of secondary surface on the air side of the heat exchanger to extract or reject heat and reducing the air side pressure drop. The tubes used in this construction are flat and segmented into very small flow channels as seen in Figure 4.

Representative Cross-section of Microchannel Heat Exchanger Core Tube



Typical Tube Depths - 13.5mm., 18.8mm., 27.1mm. Typical Tube Height - 1.91mm. Hydraulic Diameters - 0.51mm., thru 1.8mm.

Figure 4.

These flat tubes have a dual effect of reducing the air side pressure drop while maximizing the surface contact area of the tube (when compared to a round tube). This new design significantly reduced the overall size of the heat exchanger while actually enhancing heat transfer performance and minimizing the power required to move the air through the heat exchanger.

Cross-section of a Microchannel Heat Exchanger

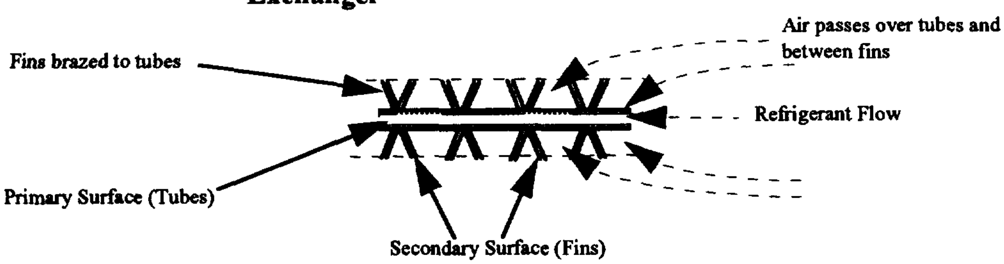


Figure 5.

Although not to scale, the relative proportions of Figures 3 and 5 are representative. The microchannel heat exchanger utilizes fins which are considerably shorter than those found in a typical round tube plate fin heat exchanger. There is a higher percentage of primary surface in a microchannel heat exchanger than what is found typically in a round tube plate fin heat exchanger. And, most significantly, the fins in a microchannel heat exchanger are metallurgically bonded to the primary surface. A cross-section of a portion of a microchannel heat exchanger is shown in Figure 6.

CROSS-SECTION OF MICROCHANNEL HEAT EXCHANGER

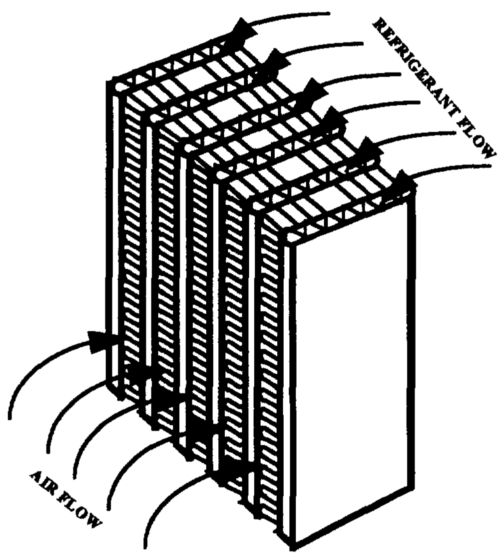


FIGURE 6

If the two heat exchanger technologies are compared with respect to the preceding discussion on the fundamentals of good heat exchanger design, it is noted that:

- the thermal gradients are significantly reduced in a microchannel heat exchanger
- the contact resistance between the fins and tubes is generally insignificant in a microchannel heat exchanger

From an environmental perspective, there are two additional advantages inherent in microchannel heat exchangers:

1. The heat exchanger is all aluminum. When the product must be scrapped it is fully recyclable.
2. Because of the reduced internal volume of the heat exchanger, the amount of refrigerant used in an air conditioning system equipped with microchannel heat exchangers is typically reduced by 50%.

From a system performance perspective, there are two significant advantages:

1. The transient response time of the system is sharply reduced over that of a conventional system due to the low mass of refrigerant in the system as well as the low mass of material in the heat exchangers. This means that the system will reach operating temperature (and therefore, do more cooling for a given time period) than in a conventional system.
2. As noted earlier in the discussion on dehumidification, reduced thermal gradients and large amounts of primary surface lead to a lower average metal temperatures in the microchannel heat exchanger. This lower metal temperature means more air comes in contact with metal temperatures below the dew point of the air, thus improving dehumidification by a factor of 20% to 30%.

Impact of the Microchannel Heat Exchanger on the Automotive Industry

During the 1980's and into the 90's, the U.S. Automotive Industry was faced with two major external challenges:

1. Improve fuel economy
2. Eliminate CFC's from the automobile air conditioning system

Many approaches were taken to improve fuel economy including a restyling of the exterior of the automobile in an effort to improve the aerodynamics of the vehicle. A major outcome of this effort was to slope the automobile's hood. Unfortunately, this caused a significant reduction in the space available for the automobile's air conditioning condenser. At the same time, the new refrigerant of choice, R134a, required more performance out of the condenser in order to maintain the same level of efficiency.

Over the past 10 years, virtually every automobile manufacturer has either adopted the microchannel heat exchanger design or created a "clone" to provide a similar level of performance as the microchannel heat exchanger. The overwhelming acceptance and success of this style of heat exchanger is based on:

- significant performance improvements
- cost effective manufacturing
- proven durability in severe environments
- proven reliability

The Building HVAC Industry

Application of Microchannel Heat Exchanger Technology to the Building HVAC Industry

With the success of the microchannel heat exchanger design in the automotive world, our researchers began to investigate the potential for applying this same technology to the building heating, ventilating, and air conditioning (HVAC) industry. The results of these efforts have been a mixture of technical successes and market frustrations.

Back in the early 1990's, investigations into the suitability of the microchannel heat exchanger in building HVAC applications were launched. The first application objective was to replace a standard "A" coil evaporator with a bent microchannel heat exchanger slab. A sketch of this bent microchannel heat exchanger (now known as the PFV™ Heat Exchanger) is shown Figure 7.

The PFV ™ Heat Exchanger

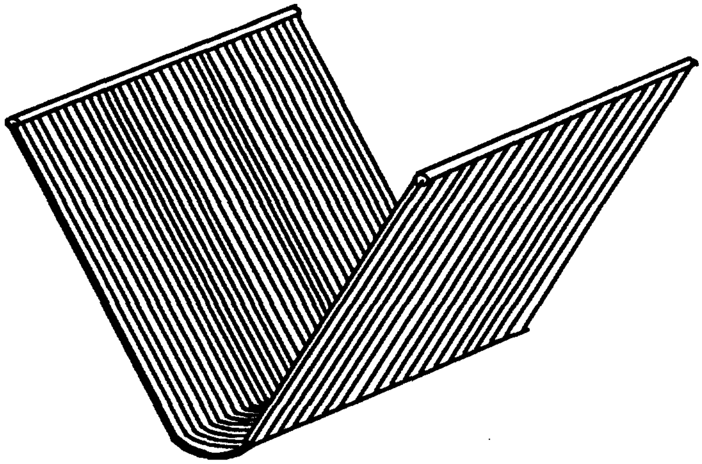


Figure 7.

The motivation behind this effort was to replace a labor intensive, complicated component with a simpler, cleaner design. The bent microchannel heat exchanger appeared to not only meet the cost objectives but also improved dehumidification with lower power requirements to move the air across the surface. The product clearly has the potential to be a cost effective replacement for the current technology as well as significantly improving comfort in the vast majority of the United States and with less power required from the blower. This significant first step led to a decision to test the design further. Since the original test work, the bent microchannel heat exchanger has been:

- tested successfully in heat pump systems (laboratory and field tests)
- tested successfully for water disentrainment (in a more challenging horizontal air handler configuration)
- tested successfully in laboratory corrosion tests
- tested successfully in system level field tests

Experimental Work

Despite all of the apparent design and cost advantages of the technology, the response by the HVAC Industry has been "lukewarm", at best. In order to continue the development effort, researchers constructed a modified central air conditioning system. A commercially available small condensing unit (outdoor unit) was purchased in which the condenser was replaced with a microchannel condenser. The original compressor was replaced with a smaller compressor. The original condensing unit began as a 10 SEER, 3 ton unit. Due to the unique application, it was not known at the time how the new condenser would perform. The modified system, therefore, was configured as a 2.5 ton system. The results of this effort were impressive. The new system was small, lightweight, delivered 30 % more dehumidification, and achieved a SEER of 13.3. Tests performed at an independent laboratory confirmed the following results:

Table 1. Test Results from Prototype Air Conditioning System using Microchannel Heat Exchangers

DOE Test	Total Cooling Capacity (BTUH)	Latent Cooling (%)	Power Input (Watts)	EER (Btu/W-hr)	Condensing Unit Pressure (psig)	Suction Pressure (psig)	Evaporator Air Side Pressure Drop (in. H_2O)
A	31350	35	2800	11.20	235	83	0.12
B	33390	37	2460	13.57	187	81	0.12
C	29570	0	2455	11.51	181	71	0.10

DOE Test	Cooling (BTUH)	Energy Input (W-hr)	EER (Btu/W-hr)	Cooling Load Factor (CLF)	Degradation Coefficient (C_D)	Part Load Factor PLF(0.5)	SEER (Btu/W-hr)
D	2722	246	11.07	0.192	0.048	0.976	13.25

Over the past several years, the bent microchannel evaporator has been tested extensively for its dehumidification characteristics. In comparison with typical round tube plate fin evaporators, the bent microchannel evaporator has consistently shown higher levels of dehumidification. A summary of a number of these tests is shown in Figure 8.

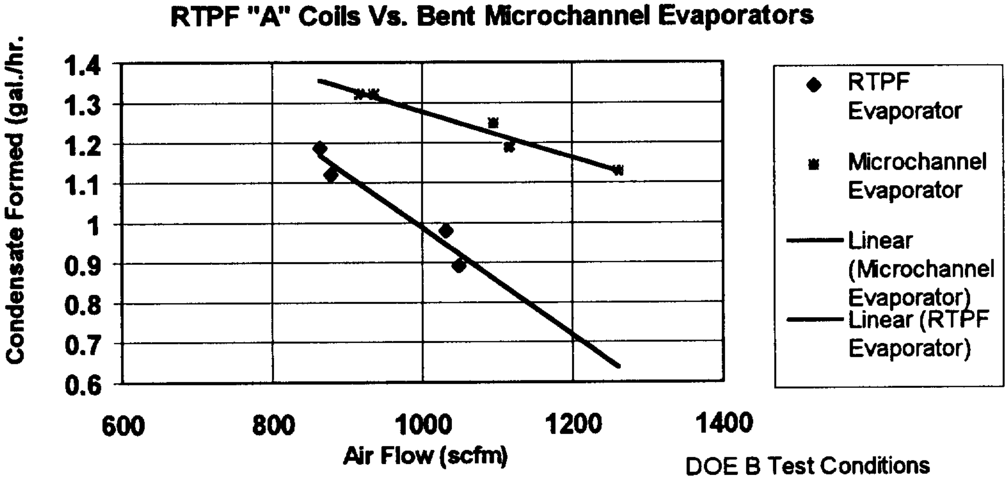


Figure 8

A limited number of field tests have been conducted. Four systems were built and placed in 3 locations around the country (Milwaukee, Wisconsin, Charleston, South Carolina, and Laredo, Texas) in the summer of 1994. One system used R-134a refrigerant, the others used R-22 refrigerant. Today, all of the systems are still in operation except the R-134a system. This unit was removed from service due to a vibration failure (unrelated to the heat exchangers).

Preliminary efforts have also been undertaken to develop a heat pump utilizing microchannel heat exchangers. Rather than retrofitting an existing heat pump, however, researchers chose to construct an entirely new system in order to exploit some of the basic characteristics of microchannel heat exchanger design.

Efficiency levels for this 2.5 ton heat pump system are as follows:

- 11.02 SEER •7.53 HSPF

The test results for this first prototype design were considered satisfactory and many design/performance enhancements were identified in the process. Work is ongoing at the time of this writing to incorporate these enhancements into the second generation of heat pump designs.

Once design and performance parameters have been satisfied, the next (and in some cases, the primary) focus is the durability and reliability of the heat exchangers. Controlled laboratory testing provides an ongoing means of product evaluation. The laboratory tests performed on microchannel heat exchangers to date include:

- neutral salt spray
- CASS (Copper Accelerated Salt Spray)
- SWAAT (Sea Water Acidified Accelerated Test)
- various proprietary test procedures

In an effort to evaluate microchannel heat exchangers in an aggressive but controlled field test for corrosion and durability, 31 window air conditioners were retrofitted with microchannel condensers early in 1997. Control and experimental units were placed in an industry-recognized field test site in Kure Beach, North Carolina. Kure Beach is considered to be one of the more aggressive corrosion test sites in North America. The condensers used in these experimental units were constructed with a variety of materials and different methods of corrosion protection in order to determine the best combination of alloys and brazing techniques. At the time of this writing, no units have experienced failure. This work is expected to be completed by the end of 1999.

Cost Analysis

For a new technology to gain acceptance in the marketplace, costs (or more realistically, selling price) of that new technology must be affordable to the average consumer. In order to assess this aspect of the problem in more detail, system cost estimates were generated comparing central air conditioning systems constructed with microchannel heat exchangers to those constructed with conventional heat exchangers. While it is clear that there are many ways to achieve high SEER values, the systems evaluated in this analysis were relatively straightforward utilizing single speed compressors, single speed fans, and basic electro-mechanical controls. Of significance in this evaluation is the effect of mark-up on the final pricing to the consumer. Following is a summary of the cost evaluation along with a chart (Figure 9) examining the impact of these costs and subsequent payback in light of various mark-ups to the consumer. This last point is especially important today since high SEER products are generally marketed at premium pricing levels.

Table 2. Estimated Factory Costs for a Residential 2.5 Ton Central Air Conditioning System*

Efficiency Level	Typical System constructed with Round Tube Plate Fin Heat Exchangers	Advanced System constructed with PF™ Heat Exchangers
10 SEER	$298	$276
12 SEER	$349	$319
14 SEER	$379	$347

*System is defined as the condensing unit and evaporator assembly (not the complete air handler)

Estimated Payback Period for Conventional Systems and Systems Constructed of Microchannel Heat Exchangers as a Function of Mark-up

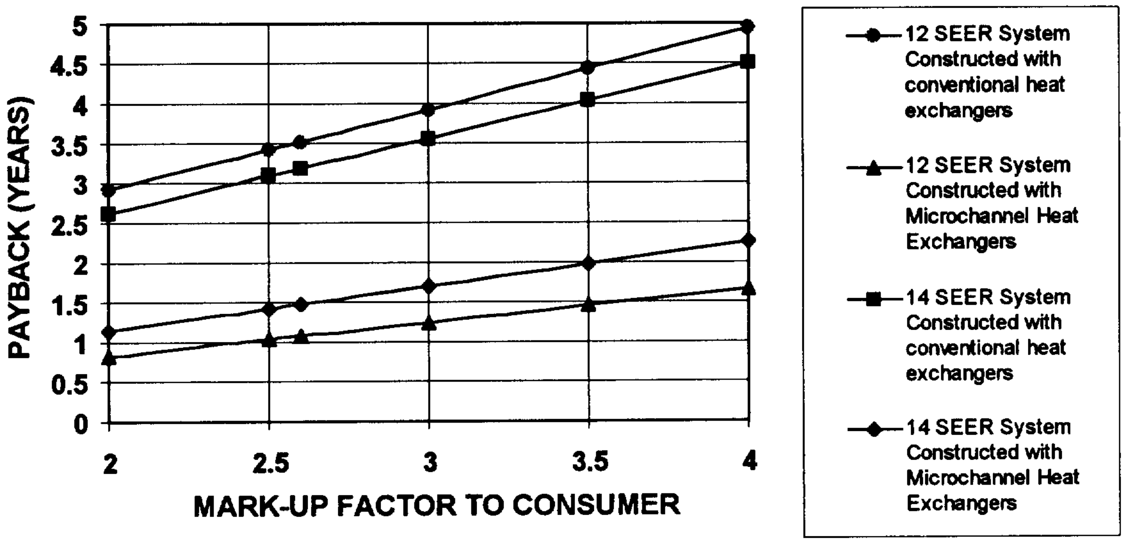


Figure 9

The Regulatory Process

A point of contention between the DOE and the HVAC industry has been the Design Options selected for each product class. Design Options typically represent new technology which is believed to be relevant and appropriate for inclusion in the rulemaking process. However, most Design Options come with a price tag to industry. Adoption of new technology can result in:

- stranded assets
- advanced in-house technology expertise needed
- the requirement for new sales and marketing tools
- higher product costs

In short, to some manufacturers Design Options are a threat to the way they prefer to do business. Because of the controversy surrounding this criterion, the DOE in cooperation with representative manufacturers of the U.S. appliance industry developed a set of criteria to be used in the evaluation process. It is worth reviewing these rules as they relate to the state of microchannel heat exchanger developments:

Criteria	Microchannel Heat Exchanger Relevance
Technically Feasible	• Application into Worldwide automotive market • Development work in HVAC&R markets
Practical to manufacture, install and service	• Design is simple and straightforward • Worldwide manufacturing facilities exist today • Extensive laboratory and field test experiences • Connections and repairs are similar to or simplified from current technology
Have no adverse impacts on product utility to the consumer	• Integration of microchannel heat exchangers into residential air conditioning is virtually transparent to the consumer • Differences between microchannel and round tube plate fin heat exchangers provide performance advantages to the consumer • Durability is greater than the current technology
Have no adverse impacts on health and safety	• No dangers to the consumer from the product • Reduced charge lessens any potential for danger even if flammable or toxic refrigerants are ever employed • The product is completely recyclable • No chlorinated solvents or lubricants used in the manufacturing process

National Field Test Program Initiative

Modine introduced the microchannel heat exchanger technology to the DOE, various state energy offices, the U.S. Environmental Protection Association, and various electric utilities beginning in 1994. Following these presentations and an expressed high level of interest in the technology, a program to develop a national field test program was established. The original objective of the program was to place up to 24 different central air conditioning systems around the country over the ensuing 6 months. It was believed that this approach would give fundamental credibility to the tenet that the microchannel heat exchanger was appropriate for the central air conditioning market. This program has gotten off to a slower than expected start but continues forward. Today, Southern California Edison has installed 2 units in their service territory. Virginia Power has funded the testing of a unit at the Florida Solar Energy Center. Programs are expected to be initiated in Wisconsin Electric's territory as well as regions of North Carolina under the auspices of the Energy Office of the Department of Commerce in North Carolina. This program is expected to last for three years. Due to the delays in the program startup, however, it is anticipated that the overall timeline will last well beyond the three year period.

Independent Evaluations

The microchannel heat exchanger has also generated interest in the academic sector over the past decade. In addition to the National Field Test Program, additional work continues at various research centers around the nation.

University of Illinois - ACRC

The Air Conditioning and Refrigeration Center located at the University of Illinois (Urbana) is testing a 2.5 ton residential split system heat pump using microchannel heat exchanger technology which is optimized around minimum TEWI (Total Equivalent Warming Impact). The system, designed to operate with HFC R410a, has been optimized to minimize the ratio of TEWI/Q_{Load} (kg CO_2/ton-hr). In this challenging program, not only is cycle efficiency a key parameter (indirect equivalent warming impact), but also the design of the system is centered around a goal of minimal refrigerant charge (direct equivalent warming impact). The objective of the ACRC program is to develop a heat pump system with an EER of 12.8 or greater combined with a 67 to 75 percent reduction in refrigerant charge.

Argonne National Laboratory

In an effort aimed at gaining a better understanding of the physics involved in microchannel heat transfer and to characterize refrigerant condensation phenomena in microchannel tubes, extensive testwork was conducted through a Cooperative Research & Development Agreement (CRADA) at Argonne National Laboratory. The condenser test facility was designed and developed in order to measure the condensation characteristics of R-12, R-22, R134a & R410a in microchannel condenser tubes.

Independent Laboratory Tests

In addition to the original central air conditioning system constructed in 1993, a second system equipped with a microchannel condenser and a bent microchannel evaporator has since been constructed and tested. The condensing unit used in the retrofit was selected on the basis of minimal footprint. Although a 3 ton system was chosen, no effort was made to achieve 3 tons of cooling. Because the goal of the test work was to achieve as high of an efficiency as possible in as small of a footprint as possible, the framework of the 3 ton unit was selected as the retrofit size target. It should be noted that the footprint of the 3 ton system was the same as the 2.5 ton test system and the compressor capacity was lowered to 2.5 tons. The only difference in the 3 ton commercial system and the 2.5 ton commercial system was a decrease in condenser height of about 4 inches for the 2.5 ton system.

Following is a comparison summary of the test system and the original system.

Measured Parameter	Modified Central Air Conditioning System using PF™ Heat Exchangers	Original System
Capacity	30,000 BTUH	36,000 BTUH
SEER	13.1	10.0
Refrigerant	R-22	R-22
Sensible Heat Ratio (@ DOE A condition)	0.64	0.724
Refrigerant Charge	82 ounces	123 ounces

Conclusions

The microchannel heat exchanger represents a significant advance in heat exchanger design over that of the round tube plate fin heat exchanger when used in refrigerant to air heat transfer equipment. The fundamentals of the technology are straightforward and "attack" the inherent weak spots of the current technology through basic improvements. These improvements have been demonstrated to achieve unexpected performance improvements in virtually every aspect of the heat transfer system.

The microchannel heat exchanger has had a short but phenomenally successful history in the automotive air conditioning market. This same basic technology has been demonstrated to be applicable to the Building HVAC market in the United States. Laboratory and field test work have demonstrated the suitability of the product in virtually every aspect of importance including but not limited to:

- heat transfer
- pressure drops
- dehumidification
- reduced refrigerant charge
- weight
- recyclability
- corrosion resistance
- durability

The product can be integrated into the same basic system and package used today with very little modification. The product is cost-effective and available to the industry as either a purchased component or a (non-exclusive) licensed technology.