RESEARCH NEEDS IN AIR-CONDITIONING AND REFRIGERATION
How Can We Use New Refrigerants Effectively?

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ABSTRACT

The depletion of stratospheric ozone has led to phase-out dates for chlorofluorocarbons (CFCs) as well as hydrochlorofluorocarbons (HCFCs), the refrigerants used in most air-conditioning and refrigeration systems in service in the United States today. Global warming concerns create interest in higher efficiencies for equipment using the successor refrigerants now under development. Systems utilizing these new refrigerants require improvements in heat transfer and fluid flow technology to achieve good performance and equipment reliability, which is vital for human comfort and commerce.

This paper describes a number of specific research needs created by the change in refrigerants and the desire for maintaining or increasing energy efficiency. Programs funded by government agencies and industry organizations are described, with emphasis on current research efforts and the need for work to follow. The purpose of the paper is to stimulate interest in these research opportunities.

INTRODUCTION

The air-conditioning and refrigeration industry is a microcosm of America. Many of the big issues that are being discussed in America today impact cooling and refrigeration products: the environment, conservation, public health, international competitiveness, a trained labor force, and the economy. Of course, these days environmental factors dominate — particularly the role of refrigerants in depleting the stratospheric ozone layer.

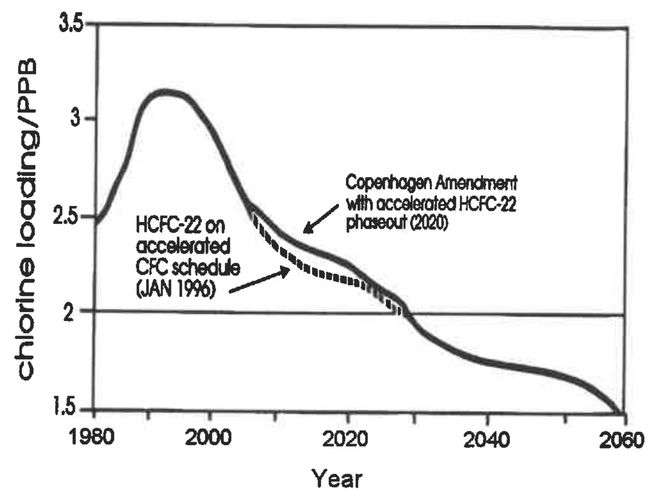

FIGURE 1. STRATOSPHERIC CHLORINE LOADING (EXISTING COMPOUNDS - ACCELERATED SCHEDULES)[1]

As a result of recent global attention to ozone depletion, international agreements for the banning of CFCs are now in place and the era of CFC production is swiftly drawing to a close. The collective goal of these agreements is to lower the amount of chlorine in the stratosphere. Stratospheric chlorine, linked to the emissions of chlorine-containing chemicals, is one of the causes of ozone depletion.

Figure 1 shows an estimate of the level of chlorine in the stratosphere over the next six decades, the so-called "chlorine loading" factor. The heavy line shows the increase, and then expected decrease, in chlorine loading due to the international phaseout of CFCs and HCFCs. Due to the relatively long atmo-

[1] Constructed from data in *Scientific Assessment of Stratospheric Ozone*, Rpt. No. 25, (Geneva: World Meteorological Organization, Global Research and Monitoring Project, 1991).

spheric lifetimes of some of these refrigerant compounds, it is predicted to require decades for the chlorine loading level to drop back to its pre-1979 level of two parts-per-billion — even after factoring in a CFC production ban starting 1 January 1996 and a HCFC production ban in 2030 (2020 for HCFC-22). The dashed line represents additional decreases in chlorine loading if HCFC-22 is also phased-out in 1996. Since HCFCs have only a fraction of the ozone depletion effects of CFCs (1/20th to 1/50th), their premature phase-out would offer minimal long-term benefits. In analyzing environmental issues, it is assumed that all refrigerants will eventually find their way into the upper atmosphere, even those in hermetically sealed systems. This may or may not occur, based on the effectiveness of refrigerant recycling, reclamation, and destruction programs.

For all intents and purposes, CFCs are out of the picture, and HCFCs have a limited future as transitional refrigerants. Beyond these refrigerants are hydrofluorocarbons (HFCs) and other compounds not containing chlorine.

Another environmental issue that the industry must address is global warming. While only a few scientists still debate the magnitude of the ozone depletion problem, many dispute whether there is sufficient evidence to act on global warming. However, the policy direction from Washington is that man-made emissions of CO_2, and other gasses adding to the greenhouse blanket that circles our planet, are likely to have sufficient global warming consequences to warrant action now, even if we are not completely certain that the problem exists.

Refrigerants that do not contribute to the stratospheric chlorine levels could contribute to the global warming effect. In referring to Figure 2, it can be seen that trade-offs between ozone depletion and global warming potentials are required. Yet, one more complication of the global warming issue is that policy makers must differentiate between direct emissions of global warming gasses; i.e., refrigerants that leak and find their way to the stratosphere, and indirect emissions, such as the CO_2 spewed from the powerplant that is producing electricity to drive the cooling equipment.

Since most systems are very tight and do not leak much refrigerant, the amount of indirect CO_2 emissions from powerplants dwarfs the effect of direct emissions from cooling equipment. As a result, the air-conditioning and refrigeration industry believes that attention needs to be focused on the efficiency of equipment, rather than only focusing on utilizing refrigerants with the lowest global warming potential. Said another way, it may be better to use a refrigerant that has a high global warming potential if it results in a more efficiently operated machine. However, industry also believes that parallel efforts must be expanded to make the systems even more leak-free.

REFRIGERATION CYCLE REVIEW

The purpose of air-conditioning and refrigeration equipment is to provide conditioned air or water — whether it be for comfort cooling

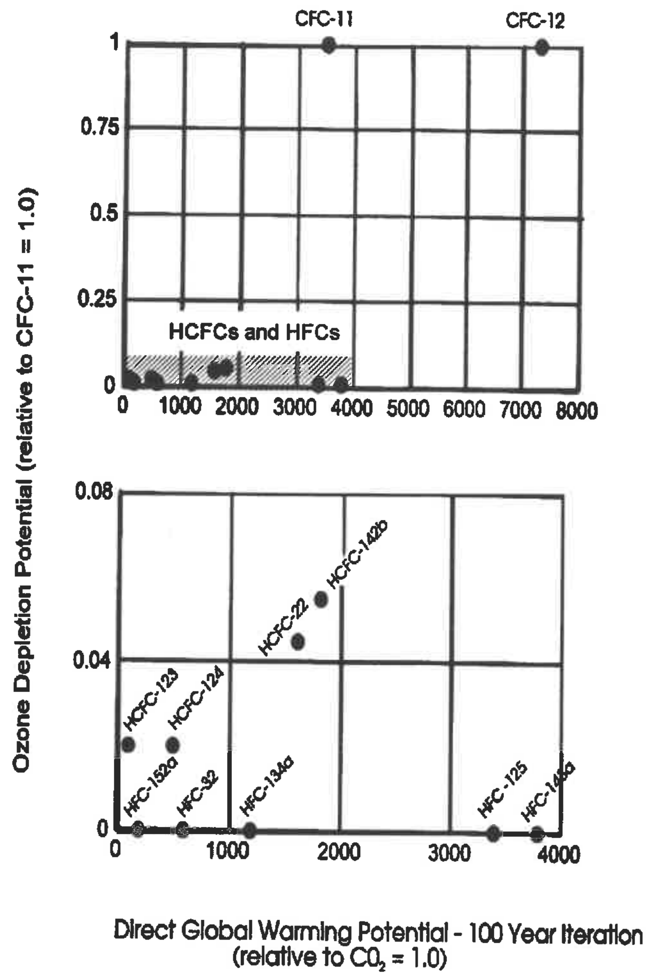

FIGURE 2. ENVIRONMENTAL IMPACT OF REFRIGERANTS[2]

or process refrigeration. Figure 3 illustrates a simple air-conditioning cycle. Beginning with the evaporator, a fan blows air that has returned from the space being conditioned (hence, this air is slightly elevated in temperature) over the cooling coil. Heat will travel from the warm air to the fins and coils cooled by the refrigerant within the system, causing the liquid refrigerant to "boil" or evaporate, changing it to a vapor. This is the cooling effect. The resultant low pressure, low temperature vapor moves to the compressor, where it is compressed into a high temperature, high pressure vapor. The compressor is where work is put into the system. The compressor then discharges the refrigerant to the condenser. The refrigerant vapor entering the condenser is at a higher temperature than the outdoor air that is passing over the fins of the condenser. Hence, heat is transferred from the hot refrigerant vapor to the relatively cool outdoor air. This is where heat is dumped. The fourth major component in a simple cycle is the pressure-reducing device that controls the flow of the refrigerant. The reduction in pressure also

[2] Constructed from data in *Scientific Assessment of Stratospheric Ozone*, Rpt. No. 20, (Geneva: Global Research and Monitoring Project, World Meteorological Organization, 1989).

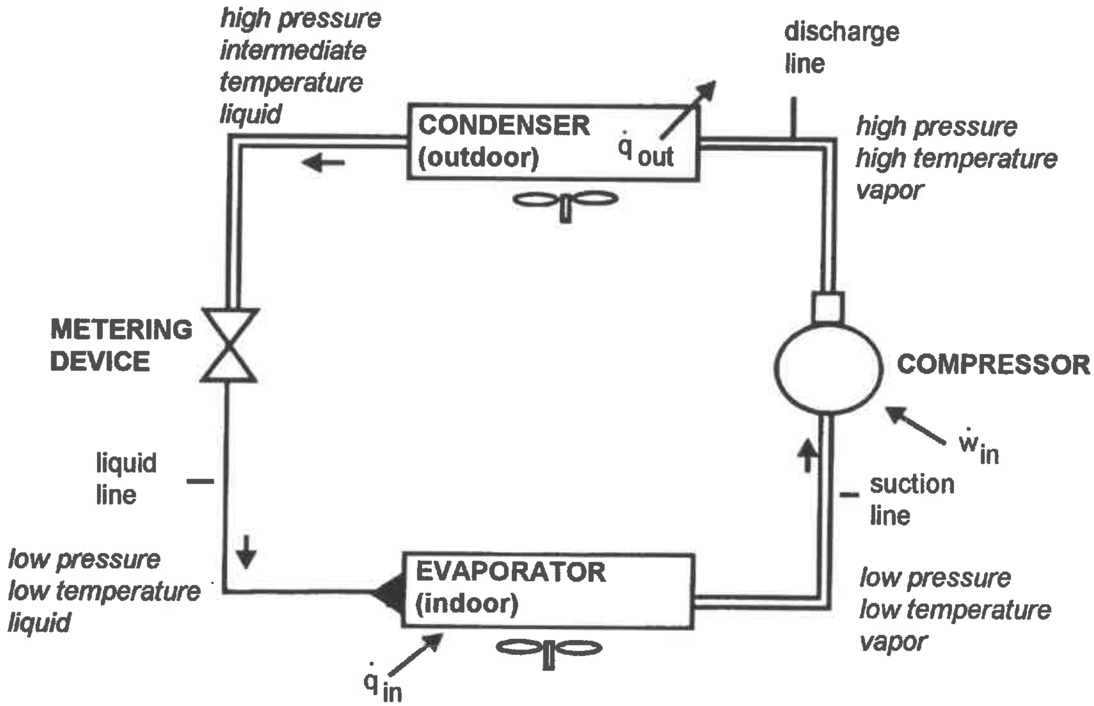

FIGURE 3. SIMPLE AIR-CONDITIONING CYCLE

drops the temperature at which the refrigerant will boil. The refrigerant leaves the pressure-reducing device as a low pressure, low temperature liquid and enters the evaporator, where the entire process begins all over again.

This simple cycle can provide heat as well. In "reverse-cycle," or heat pump applications, the indoor heat exchanger acts like a condenser and rejects heat to the conditioned space while the outdoor heat exchanger receives heat from outdoors. However, a few more components -- such as a suction-side accumulator, reversing valve, check valves around the expansion device, and additional piping -- are required to allow this reverse operations.

TECHNICAL PROBLEM OVERVIEW

Now, let us look in more detail at these components within the system and see the challenges that need to be overcome to utilize alternative refrigerants.

Heat Exchangers:

Air-conditioning and refrigeration systems use a variety of heat exchanger configurations to accomplish cooling or heating. In the most common systems, refrigerants which are evaporating (i.e., boiling) or condensing form one partner in the heat transfer process. The other partner is the "fluid" to be cooled or heated, which may be water, air, or brine.

Refrigerant evaporation can be performed in various types of heat exchanger configurations. They can be direct expansion types where the refrigerant flows inside the heat exchanger tubes and the air or water flows past the outside of the tubes. Alternatively, they can be of the flooded type where water runs through tubes and the refrigerant is allowed to pool inside the shell of the heat exchanger. Similarly, refrigerant condensation can take place within a tube, with air or water on the outside to remove the heat; or a liquid can be routed through the tube, with condensation taking place on the outside tube surface. Since both the evaporator and the condenser perform similar roles, and, in heat pump equipment they actually reverse roles, they can look similar.

Heat exchangers generally employ extended surfaces designed to increase heat transfer. To increase efficiency, it is important that the quantity of heat transferred between the two fluids is maximized. Yet, there are trade-offs associated with this action. For example, as fins are made larger, more numerous, and with extended or perturbed surfaces, the pressure drop of the fluid moving across that surface increases. This increase in pressure drop will result in increased fan or pump power, and can offset any efficiency gains provided by the better heat transfer surface. Complicating the problem further, evaporators that cool air directly (e.g., direct expansion evaporators) generally have moisture condensation on the fin surfaces, thereby increasing the air-flow pressure drop while degrading heat transfer performance.

Research is needed to ascertain proper tube augmentation, both on the inside and the outside of the tube, to obtain optimum fluid mechanics leading to the maximum heat transfer at minimum friction losses. This requires a better understanding of the boiling and condensing heat transfer mechanisms. Additionally, a better model of how basic heat exchanger geometries affect turbulence, pressure drops, and heat transfer coefficients is needed.

Many of the proposed alternative refrigerants are actually blends of two or more separate fluids that may not stay uniformly mixed throughout the full air-conditioning cycle. If these formulations, once blended, do not act as one fluid — that is, they have a tendency to separate into separate components — they are called zeotropes. Unlike pure fluids, or azeotropic blends that act like pure fluids, these zeotropic mixtures will evaporate and condense over a range of temperatures at a given pressure. This characteristic is known as "refrigerant glide." When the glide is small (approximately 5 °F or less), the refrigerant acts almost like a pure fluid and can utilize standard heat exchangers with minimal efficiency penalties. Refrigerants with large temperature glides are more difficult to use in existing equipment. However, these large-glide refrigerants offer an opportunity to match their temperature characteristics to specific applications if counter-flow heat exchangers can be utilized.

Correct application of counter-flow heat exchangers can actually increase performance. However, when utilizing counter-flow heat exchangers, a situation can develop in which the temperature of the refrigerant within the heat exchanger approaches that of the fluid outside. At this so-called "pinch" point, no additional transfer of heat will occur, even though heat exchanger surface is available. It should be noted that fabrication of "true" counter-flow heat exchangers can be expensive.

The very lubricant used to ensure reliable compressor operation can have a detrimental effect on heat transfer. The lubricant entrained within the refrigerant can coat heat exchanger surfaces and prevent efficient transfer of heat; particularly for enhanced surfaces. Hence, it is necessary to understand what happens to heat transfer as a result of oil films and subsequent clogging of heat exchanger augmentation devices.

Heat exchangers in air-conditioning and refrigeration equipment are significant elements determining system size, cost, energy consumption, and level of refrigerant charge. Significant research opportunities remain to obtain a better understanding of heat transfer mechanics with pure fluids and blends of refrigerants, with and without lubricants.

Compressors:

The heat exchangers, as acceptors and rejecters of heat, represent the true purpose of air-conditioning and refrigeration equipment. However, it is the compressor that enables the system to function. The compressor is frequently referred to as the "heart" of the system because it circulates the refrigerant through the equipment and "pumps" the refrigerant from one pressure to another. There are a number of design problems that have to be overcome to adapt existing compressor technologies to alternative refrigerant applications. The role of fluid mechanics in the design of efficient compressors cannot be overemphasized.

There are two basic types of compressors. One type is positive displacement machines such as reciprocating compressors, scroll compressors, screw compressors, and rotary compressors. These compressors utilize a piston or some other mechanical displacement device to physically reduce the volume, thus squeezing or compressing the refrigerant. The second type is a dynamic compressor, such as the centrifugal compressor, which compresses the refrigerant using centrifugal force.

To maintain energy efficiency and mechanical integrity in positive displacement machines, compressor discharge valves will need redesigning to reflect the different volumetric capacities of the alternative fluids. Valve redesign is a complex problem that demands detailed fluid flow and structural dynamic analysis to obtain satisfactory results in terms of efficiency and reliability. Additionally, since the discharge pressure of an alternative refrigerant will vary dependent on the pressure-volume-temperature characteristics of the fluid and the level of compression that needs to be performed on the gas, the discharge port configuration will also require analysis and redesign to achieve optimum flow characteristics. It should be noted that valve and port design can significantly affect flow noise and pressure pulsations within a compressor.

In centrifugal compressors, improvements to the aerodynamic configurations of the impeller are required to reduce dynamic friction losses within the compressor and to maximize refrigerant gas flow.

Oil is used in the compressor to lubricate bearings, seal component clearances, remove some of the heat of compression, and reduce compressor noise. However, some of the lubricant is entrained within the discharge gas and is transported throughout the system. To minimize the amount of oil that is logged through the system, thereby causing performance penalties in the heat exchangers, novel designs of oil separators are required. Not only will efficient low-pressure drop oil separators improve the overall performance of the system, but they will also enable more compact systems to be constructed. What is more desirable are oil-less bearings, or perhaps oil-less compressors, so that entire systems can be operated without oil. Removal of oil from the system may improve heat exchanger performance. Unfortunately, the manner to reliably adapt oil-free compressors in air-conditioning and refrigeration equipment has eluded the industry. Perhaps electromagnetic bearings or liquid refrigerant, as a substitute for oil, can be utilized. A successful solution to removing oil from the compressor would greatly simplify refrigerant selection and system design since refrigerant-lubricant miscibility and solubility requirements would be eliminated.

Positive displacement and dynamic compressors are of the open- or hermetic-drive type. In hermetic compressors, the motor is exposed to the refrigerant flowing through the compressor. The refrigerant flow keeps the motor cool and operating efficiently. Hence, a hermetic motor must utilize construction materials that are compatible with the refrigerant and lubricant. This is not always an easy task since many refrigerants are also excellent solvents. Open drive machines, where the motor is located external to the compressor, require shaft seals to prevent the refrigerant from leaking around the drive shaft. Again, the materials of construction need to be compatible with the fluids in the system. Since lip seals and shaft mating surfaces are subject to high-speed and high-temperature conditions, acceptable wear and mechanical integrity requirements need to be investigated. New sealing technologies that minimize friction and promise zero emissions require research.

Other Concerns:

The entire system faces concerns that have to be resolved. Many of the alternative refrigerants will result in higher discharge pressures and discharge temperatures for a given duty cycle. Hence, beyond simple mechanical integrity of the design, there is also a concern for the long-term stability of the refrigerant and lubricant within the system. Will the refrigerant or lubricant break down? If so, to what extent? And will the resultant by-products effect long-term system performance, system reliability or technician safety?

Another concern when utilizing zeotropic refrigerants is that, in the case of a leak, one refrigerant could preferentially boil off. This fractionation of the refrigerant would change the circulating composition of the refrigerant blend and could affect the overall efficiency. As fractionation causes one component to preferentially separate from the base blend, there also exists the possibility of a flammable situation developing -- either in the fluid left behind, or in the fluid that is leaking from the system. Hence, a possible safety issue exists. Research in evaluating the limits of this problem and in establishing a definitive flammability test is required.

Currently, slow refrigerant leaks from air-conditioning and refrigeration equipment are not noticed until sufficient refrigerant charge has escaped and a degradation in cooling performance is detected. It is usually at this point that the equipment owner calls a service technician. If there is a leak during the off-season, the entire refrigerant charge could be lost. Low-cost monitoring sensors that detect system leaks after a very minimal loss, say 2-5%, would be useful. Perhaps optical, ultrasonic, and temperature sensors can be married with an expert system to monitor equipment performance and assess if a leak has occured. Ideally, the monitoring sensor should work whether the system is in operation or not. Additionally, devices and methods that could determine the composition of the refrigerant mixture within the system would aid field service personnel considerably. Currently, only expensive laboratory measurement devices can make composition measurements. Since no portable detection or measurement tools exist for blend management, a service technician is not able to know if the refrigerant composition has been changed. Even if known, no tools are currently available that would allow a technician to successfully recharge the system to the proper specifications. Ultimately, this can lead to equipment efficiency and reliability problems.

Other Cycles:

The industry is also interested in other methods of satisfying comfort cooling and refrigeration requirements. Alternative techniques utilizing absorption, adsorption (or desiccant) and Stirling cycles are being investigated to see if they can be made as efficient as today's vapor-compression systems.

Absorption refrigeration cycles (see Figure 4 for a schematic of a typical system) are heat-operated cycles in which a secondary fluid (the absorbent) absorbs the primary fluid (gaseous refrigerant) that has been vaporized in the evaporator. Absorption proceeds because of the mixing tendency of miscible substances, and because of an affinity between absorbent and refrigerant molecules. This cycle utilizes a pump — as opposed to a compressor — to move the circulating refrigerant around the circuit. An external heat source

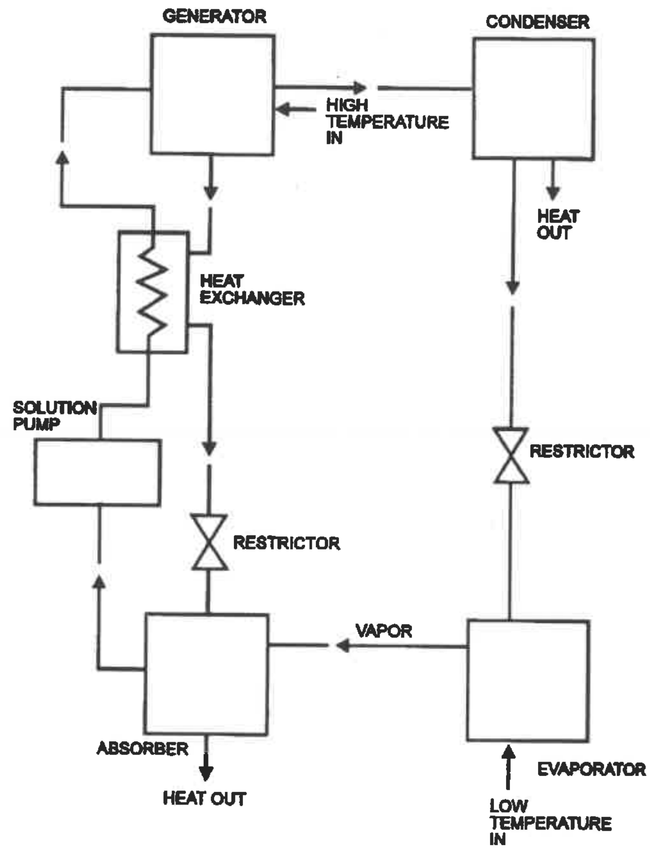

FIGURE 4. LITHIUM BROMIDE - WATER SINGLE STAGE ABSORPTION REFRIGERATION CYCLE[3]

is used for regenerating the absorbing media. Typical absorbent and refrigerant pairs have been: lithium bromide (absorber) and water (refrigerant), and water (absorber) and ammonia (refrigerant). In order to increase efficiency, designers have gone to cycle enhancements such as generator/absorber heat exchangers and cascaded systems. One of the more interesting recent advances is the so-called "triple effect cycle." Research is still needed to find suitable materials for use in high-temperature generators. Additionally, the size and cost of the equipment could be reduced if higher heat and mass transfer rates could be obtained by heat and mass transfer augmentation techniques.

In recent years there has been significant progress in regenerative solid/liquid adsorption systems. In adsorption cooling (see Figure 5 for a schematic of a typical system), a fluid is attracted to a solid or liquid desiccant. The desiccant adsorbs moisture from the air with the resultant dry, but warm, air being cooled by a heat exchange with outdoor air. The indoor air is then cooled by a water spray. Research opportunities exist in enhancing the heat exchanger wheels (e.g., making them more efficient so they can be smaller) and in providing a better desiccant material and drying method. Specific research needs are in the areas of heat/mass transfer with solid adsorbent heat exchanger media, low cost/high capacity adsorbent/

[3] "Thermodynamics and Refrigeration Cycles," *1989 ASHRAE Fundamentals Handbook*, (Atlanta: American Society of Heating, Refrigeration, and Air-Conditioning Engineers, 1989), pp. 1-21.

binder pairs, and durable, low-mass adsorbent heat exchanger designs.

Stirling cycle refrigeration has been associated with cryogenic applications, but it has not been successfully scaled-up to air-conditioning and refrigeration applications with their low temperature lifts and high energy flux requirements. Stirling engines offer high efficiency, flexibility in fuel selection, and, conceptually, durability due to the small number of moving parts. However, industry has been unable to economically apply Stirling engines and still maintain durability and reliability as compared to conventional equipment. To overcome the limiting factors associated with reliable applications of the Stirling cycle to air-conditioning and refrigeration duties, the following improvements are needed:

- develop the necessary materials and design methods to produce long-life (40,000 hours mean time between failures) seals and bearings;
- develop ways of transferring heat to the working fluid of Stirling engines that reduce or eliminate thermal-stress failure problems;
- basic research on the oscillating-flow heat transfer and pressure drop phenomena that occur in regenerators (i.e., the porous material used to recover energy from the working fluid as it is shuttled between the hot expansion and the cold compression chambers).

Newer and more innovative systems may be required in the future. To that extent, cycles that are still in their infancy require research attention. One such example of an exotic cycle is magnetic refrigeration. Advances in superconductors — with the intense magnetic fields that they produce — have spurred increased interest in this system because the energy density of the system increases with the magnetic field density.

Ancillary Research Needs:

Industry is interested in research in areas unrelated to the direct production of cold air or cold water. As an example, any power savings achieved by better air-flow in duct distribution systems will enhance overall system efficiency. Alternative designs utilizing innovative airfoil shapes and materials may increase fan efficiency and reduce noise. Creation of improved computer modeling techniques may aid in enhancing the design of fan airfoils, compressor discharge passages, and in improved heat exchanger circuiting. Obviously, better design tools will aid in better understanding of fluid-flow constraints and in providing improved systems to the consumer.

Additionally, as noted earlier in this paper, ease of equipment servicing is a major issue. It is well-recognized that today's systems are becoming more complex, but the goal is to make the systems easier for trained service personnel to diagnose and maintain. Educating service personnel and providing them with the tools that will allow them to properly convert existing CFC and HCFC equipment to the new chlorine-free alternatives are high priorities. One problem in this area is finding better ways to clean or flush out the old refrigerants and lubricants prior to utilizing the new fluids.

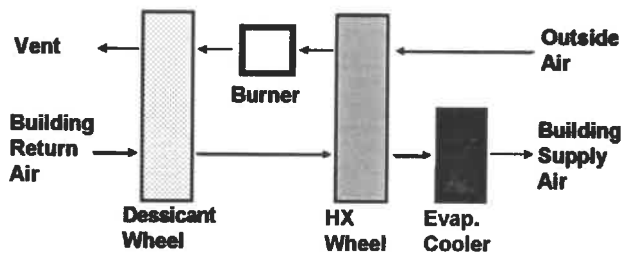

FIGURE 5. DESICCANT COOLING SYSTEM

REPRESENTATIVE WORK UNDERWAY IN HEAT TRANSFER AND FLUID FLOW

As would be expected, there is much research already underway in the areas discussed previously. For example, the Air-Conditioning and Refrigeration Technology Institute (ARTI) is managing research related to material compatibility, lubricants, and issues associated related with new refrigerants. One of the projects being funded by ARTI is a study of electrohydrodynamics (EHD) heat transfer at the University of Maryland. Early results indicate that EHD augmentation techniques may provide a substantial increase in heat transfer rates. Work is also underway to look at the performance of cross-counterflow heat exchangers, which may result in better efficiency when used in conjunction with zeotropic refrigerant blends.

A coordinated industry effort to look at possible substitutes for R-22 is resulting in air-conditioning and refrigeration equipment manufacturers sharing data on the performance of these substitutes. In conjunction with this effort, the National Institute of Standards and Technology, the University of Illinois, Iowa State University, and Lehigh University, among others, are measuring heat transfer coefficients, both in evaporation and condensation, and investigating the mechanisms of heat transfer on extended surfaces.

Utilizing the latest information, equipment manufacturers are optimizing the design of their compressors, heat exchangers and other system components for alternative refrigerants.

FUNDING ORGANIZATIONS

There are numerous organizations that fund research and development in the areas of air conditioning and refrigeration. Some are listed in Table A. While some of these organizations are exclusively involved with R&D management, others also perform R&D.

In addition, there are also a number of state agencies that support environmental and energy conservation R&D. One such organization is the New York State Energy Research and Development Agency (NYSERDA). One NYSERDA-supported program is looking at using R-134a in supermarkets. Check with your state energy office to see if they have similar programs.

ORGANIZATION AND ADDRESS	APPROXIMATE ANNUAL BUDGET FOR HVACR RE-SEARCH PROGRAMS	AREAS OF INTEREST
Air Conditioning and Refrigeration Technology Institute 4301 N. Fairfax Drive, Suite 425, Arlington, VA 22203 (703) 524-8800 Mr. Mark Menzer, Vice President, Research & Technology	$2.5 Million (From DOE Budget)	Manages a DOE research grant in the area of materials compatibility and lubricants research for alternative refrigerants.
American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) 1791 Tullie Circle, NE, Atlanta, GE 30329 (404) 636-8400 Mr. William W. Seaton, Manager of Research	$2.6 Million FY93	Comfort heating, cooling, and refrigeration; Indoor Air Quality (IAQ)
Electric Power Research Institute (EPRI) 3412 Hillview Avenue, Post Office Box 10412 Palo Alto, CA 94303 (415) 855-1033 Mr. Wayne V. Krill, P.E., Senior Project Manager, Commercial Programs	$10 Million	Electric driven cooling and refrigeration; preserving load demand side management; higher efficiency equipment; new refrigerants
Gas Research Institute 8600 West Bryn Mawr Avenue Chicago, IL 60631 (312) 339-8375 Mr. Gale H. Myers Director, Space Conditioning Research	$20 Million	Gas-fired cooling (absorption, engine driven, desiccant), adsorption, and heat pumps
U.S. Department of Energy Forrestal Building 5H-048, Mail Stop CE-422 1000 Independence Avenue, SW Washington, DC 20585 (202) 586-9130 Mr. John D. Ryan Program Manager, Office of Building Research	$9.2 Million FY93	High efficiency, electric and gas-driven equipment, alternative refrigerant material compatibility
U. S. Environmental Protection Agency AEERL/MD-62B Research Triangle Park, NC 27711 (919) 541-0590 Ms. Cynthia Gage Mechanical Engineer, Stratospheric Ozone Protection Agency	$1.5 Million	Modeling mixtures; heat pump optimization; composition measuring techniques

TABLE A. REPRESENTATIVE ORGANIZATIONS THAT FUND R&T IN THE AREAS OF AIR-CONDITIONING AND REFRIGERATION

CONCLUSION

ARI's Research and Technology Department was established to identify, influence and coordinate pre-competitive R&D. ARI can assist by screening ideas that you may have and advising equipment manufacturers about them, or by aiding you in identifying interested parties to sponsor the work.

Equipment manufacturers, either individually or collectively, may have an interest in supporting certain R&D initiatives. Through our committee structure, and through our industry publications such as *Tech Update*, ARI can advise manufacturers about your research.

The twin objectives of using environmentally-benign refrigerants and lowering equipment energy consumption provide the research and development community with many opportunities to offer technological solutions.