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REFRIGERATION IN A WORLD WITHOUT CFCs

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Abstract

In an era of heightened awareness of energy efficiency and the associated environmental impacts, many industries, worldwide, are exploring "environmentally friendly" technologies that provide equivalent or improved performance while reducing or eliminating harmful side-effects. The refrigeration and air-conditioning industry, due to its reliance on CFCs and HCFCs has invested in research in alternatives to the industry standard vapor compression machines. One alternative technology with great promise is chemical absorption. Absorption chillers offer comparable refrigeration output with reduced SO_2*,* CO_2*, and* NO_x *emissions. Additionally, absorption chillers do not use CFCs or HCFCs, refrigerants that contribute to ozone depletion and global warming.*

The purpose of this paper is to provide an introduction for those new to absorption technology as well as a discussion of selected high efficiency cycles and environmental impacts for those familiar with absorption. The introduction will include a brief history of absorption and a description of the basic refrigeration cycle, while the advanced sections will discuss triple-effect technology and a life-cycle or "systems" approach to evaluating global warming impacts.

Absorption Cycle: How Does It Work?

Absorption chillers are heat-operated refrigeration machines that operate on one of the earliest known principles of refrigeration. The cycle uses a refrigerant (known as the primary fluid), and an absorbent (known as the secondary fluid). The refrigerant (primary fluid) is chemically and physically absorbed by the absorbent (secondary fluid) for the purpose of transferring heat. The evaporation of the primary fluid removes heat, thus providing the refrigeration effect. [1]

The absorption cycle can be compared to the more familiar mechanical vapor compression cycle in that both cycles evaporate and condense a refrigerant liquid at two or more pressures within the unit. The absorption cycle uses a heat-operated generator, a heat-rejecting absorber, and a liquid solution pump (see Figure 1). Comparably, the vapor compression cycle uses a compressor to increase the refrigerant pressure (see Figure 2). The absorption cycle substitutes a physiochemical process for a purely mechanical compressor. Both cycles require energy input for operation--heat and a small amount of mechanical energy for the absorption cycle compared to strictly mechanical energy for the compression cycle. [1]

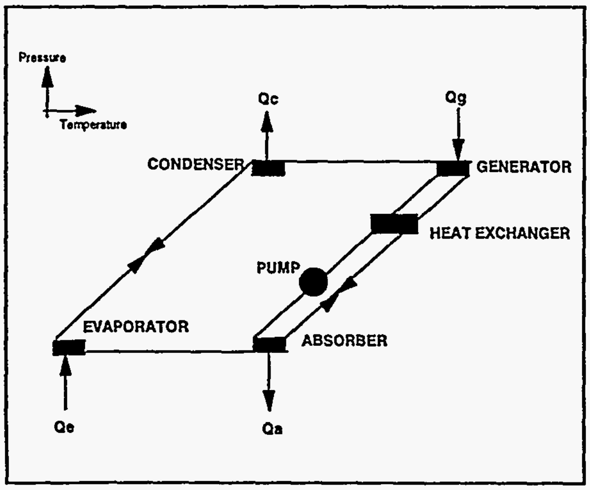

Figure 1. Single-effect Absorption Refrigeration Cycle.

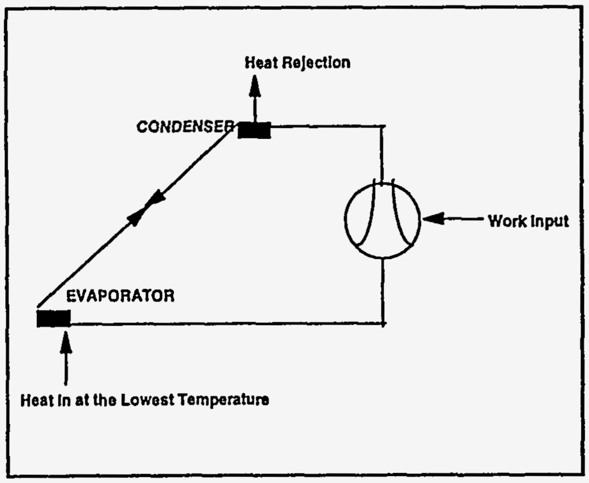

Figure 2. Vapor Compression Cycle [2].

Absorption cycles have been used in air conditioning applications for over 50 years. Ammonia-water absorption equipment was found to be well suited for large capacity industrial applications that required low temperatures for process cooling. In domestic applications, an air-cooled ammonia-water absorption cycle, with ammonia as the refrigerant and water as the absorbent, was once used in residences and is now used in recreational vehicles as a refrigerator to keep food and liquid cold. Lithium bromide/water absorption equipment is currently used to produce chilled water for space cooling and also can be used to produce hot water for indoor comfort heating, process heating, and domestic purposes. The absorption cycle can also be used as a temperature booster or heat transformer by delivering a working fluid at a temperature higher than that of the driving heat source. [1]

Many single-effect $LiBr/H_2O$ absorption chillers, using low pressure steam or hot water as the heat source, have been installed in commercial buildings to produce chilled water for air conditioning. Single-effect systems are also used to cool fluids in industrial processes, often using waste heat to power the system. The thermal efficiency of single-effect absorption systems is low. As natural gas prices increased relative to electricity over the past 20 years, the market for such chillers has decreased significantly. Although the technology is sound, the low efficiency has inhibited the cost competitiveness of single-effect systems. Most new single-effect machines are now installed in applications where waste heat is readily available.

The desire for higher efficiencies in absorption chillers led to the development of double-effect $LiBr/H_2O$ systems. These systems have been designed and manufactured to be powered by gas-fired combustors or high pressure steam. In the United States, double-effect absorption chillers are used for air conditioning and process cooling in regions where the cost of electricity is high relative to natural gas. Double-effect absorption chillers are also used in applications where high pressure steam is readily available (e.g. district heating), or in areas where seasonal electric load peaks cause utilities to subsidize gas cooling.

Triple-effect absorption chillers are proposed, and are under development, as the next step in the evolution of absorption technology. Triple-effect systems offer the possibility of thermal efficiencies equal to those of electrical chillers, while offering the ability to reduce peak electric loading and capitalize on the environmental benefits. The higher efficiency levels would open wider markets for absorption chillers and help to reduce the investment required in new electrical generation facilities by summer-peaking electric utilities.

The History of Absorption Chillers

As early as 1777, Nairne reported on absorption experiments using sulfuric acid and water [3]. By placing two bowls, one filled with water and one filled with sulfuric acid, side by side under the receiver of an air pump, he promoted forced evaporation to form ice. From those humble beginnings, "absorption" heat transfer was launched. Nairne's work was followed by the experiments of John Leslie in 1810, and the construction of ice production machines by Edmond Carré in 1850. In 1859, a breakthrough occurred with the patenting, by Ferdinand Carré, brother of Edmond, of an absorption machine using ammonia-water as the working pair. F. Carré went on to obtain 14 additional patents on absorption cycles used for ice production. From 1880 on, the vapor compression machines of Carl Linde began to displace the absorption machines. However, in the 1920's, the absorption machines experienced a renaissance. Around this time, the Europeans began looking for machines that could save energy by utilizing waste energy. The first paper on the use of absorption processes for heat pumps was published by E. Altenkirch in 1920, who first described the principles of reversible heating. A tremendous amount of the absorption technology currently in use was prescribed in papers published by Altenkirch.

The earliest reported absorption refrigeration research in the United States was carried out by McKelvy and Isaacs of the U.S. Bureau of Standards in 1920. This work and other research carried out in the United States from 1927-1974 was described in a survey by Macriss [4]. With the onset of the energy crisis in 1973, many new R&D projects emerged in the U.S. and abroad.

Developments that occurred in Europe are described in Hodgett [5], while U.S. efforts are reviewed by Hanna and Wilkinson [6]. Several of these programs were sponsored by the United States Department of Energy.

Single-Effect Cycle

The single-effect "cycle" refers to the fluid flow through the four major components of the machine (evaporator, absorber, generator, and condenser). It is common industrial practice to represent the four major components on a pressure versus temperature diagram, such as those shown in Figures 1 and 3. Single-effect chillers can be used for cooling process water and are sold in capacities from 7.5 to 1500 tons.

To describe the operation of a single-effect absorption cycle, the flow streams on the schematic diagram in Figure 1 have been numbered (see Figure 3). The

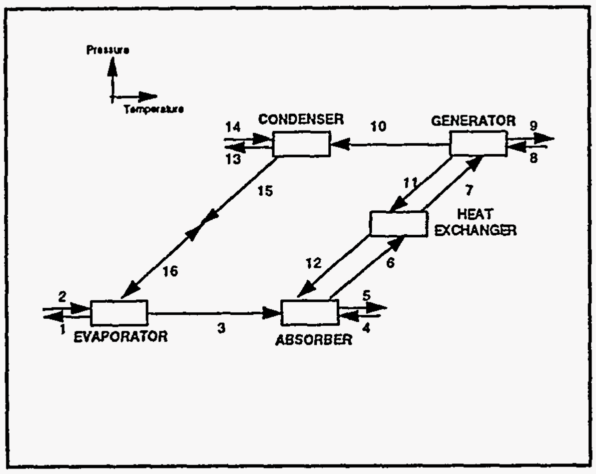

Figure 3. Single-effect Absorption Cycle Represented on a Pressure Versus Temperature Diagram

single-effect chiller uses a LiBr/H_2O solution as an absorbent and water as a refrigerant. The cycle operates as follows: stream 8 (hot water or steam) adds energy to the generator for the purpose of heating the absorbent solution (stream 11) and boiling off the refrigerant vapor (stream 10). The heating source leaves the system at a somewhat colder temperature (stream 9). The hot, concentrated absorbent solution (stream 11), in equilibrium with the condenser pressure, leaves the generator enroute to the absorber via the solution heat exchanger. In the solution heat exchanger, the hot absorbent preheats the incoming solution and flows to the absorber (stream 12). The now cold, concentrated absorbent solution absorbs low-pressure refrigerant (stream 3) in the absorber, which is in equilibrium with the evaporator pressure. The absorbent solution (stream 6) is then pumped to the generator via the solution heat exchanger, where heat is recovered from the solution leaving the generator. The preheated low concentration lithium bromide absorbent solution (stream 7) enters the generator, where heat is added to distill the H_2O refrigerant which leaves as a vapor stream (stream 10). This high pressure refrigerant vapor condenses in the condenser. Hot, liquid refrigerant (stream 15) is expanded (stream 16) into the evaporator, where it is evaporated at low pressure and temperature. The chilled water enters the evaporator (stream 1), where heat is absorbed by the refrigerant to provide the desired cooling effect, and exits at a lower temperature (stream 2). Cold, low-pressure refrigerant vapor (stream 3) is absorbed by the solution in the absorber. Streams 4-5 and 13-14 are cooling tower water used to remove heat from the absorber and condenser respectively. [7]

In operational practice, the operating envelope of the chiller is normally represented on a pressure, temperature, concentration (PTX) diagram. A detailed PTX diagram is shown in Figure 4. This diagram is

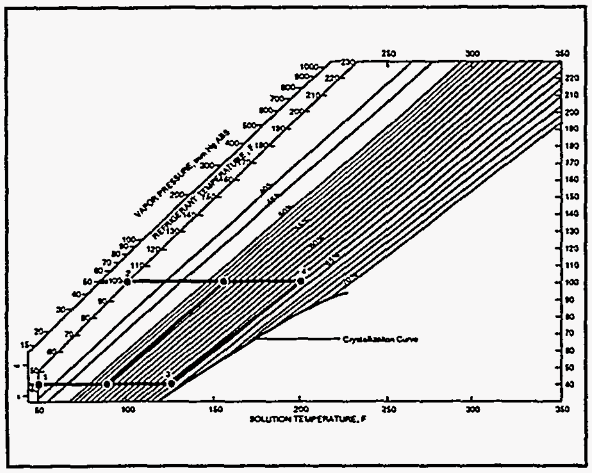

Figure 4. Single-Effect Absorption Cycle Represented on a Pressure, Temperature, Concentration (PTX) Diagram

helpful to show how the operating conditions of the single-effect chiller can be set to optimize cooling capacity and to prevent crystallization of the absorbent. The temperature of the evaporator is set by the chilled water (tubeside) temperature. Nominal output chilled water temperature to the air conditioned space is 45 °F. With an approximate 3 °F approach temperature, the refrigerant in the evaporator (shell side) is 42 °F. The pure refrigerant water line is at the left axis of the curve.

Point 1 represents the pure refrigerant temperature of 42 °F. This point fixes the evaporator pressure at approximately 7.5 mm Hg. The condenser temperature is set by the cooling tower water temperature. The nominal temperature for cooling tower water (tubeside) leaving the condenser is 95 °F. With an approximate 5°F approach temperature, the refrigerant in the condenser (shell side) is 100 °F. Point 2 represents the pure refrigerant temperature of 100 °F. This point fixes the condenser pressure at approximately 50 mm Hg. The absorber operates at the same pressure as the evaporator, and the generator operates at the same pressure as the condenser. The absorber operating conditions (point 3) are constrained by the crystallization line of the $LiBr/H_2O$ solution. The absorber operating conditions influence where the remaining component, the generator (point 4), can be positioned on the PTX diagram. The corresponding solution temperature for the generator can be read from the bottom axis. With a corresponding approach temperature, the heat input required to drive the generator can now be deduced.

Efficiencies in absorption chillers are described by the term coefficient of performance (COP), which is defined as the refrigeration effect/net heat input. Single-stage absorption machines have COPs of approximately 0.6-0.8 out of an ideal 1.0 (i.e. for every unit of heat input to the generator, 0.6-0.8 units of cooling output are produced in the evaporator). The inefficiencies can be accounted for as second law thermodynamic losses in the chiller. Since the COPs are less than one, the single-effect chillers are normally used in applications that recover waste heat such as waste steam from power plants or boilers.

Double-Effect Cycle

In the late 1950's, J. S. Swearingen and E. P. Whitlow built the world's first working double-effect $LiBr/H_2O$ absorption chiller [8].

Figure 5 represents the double-effect absorption cycle on a pressure versus temperature diagram. Although there are several variations on this cycle, Figure 6 represents a typical schematic diagram of a double-effect absorption chiller. This design is the most commonly used in manufactured products and is available with capacities ranging from 100 to 1500 tons. The double-effect chiller differs from the single-effect in that there are two condensers and two generators to allow for more refrigerant boil-off from the absorbent solution. The higher temperature generator receives the externally-supplied heat (eg. steam) that boils the refrigerant from the weak absorbent. This refrigerant vapor from the high temperature generator is condensed and the heat produced is used to provide the heat to the low temperature generator. Due to the additional recovery of heat, two units of refrigerant vapor recovery are available for only one unit of heat input. The second unit of refrigerant vapor recovery comes from the additional recovery of heat at the lower temperature.

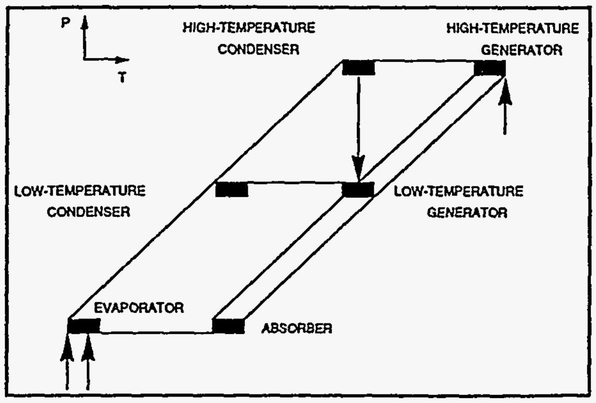

Figure 5. Double-Effect, Lithium Bromide/Water Absorption Cycle Represented on a Pressure versus Temperature Diagram

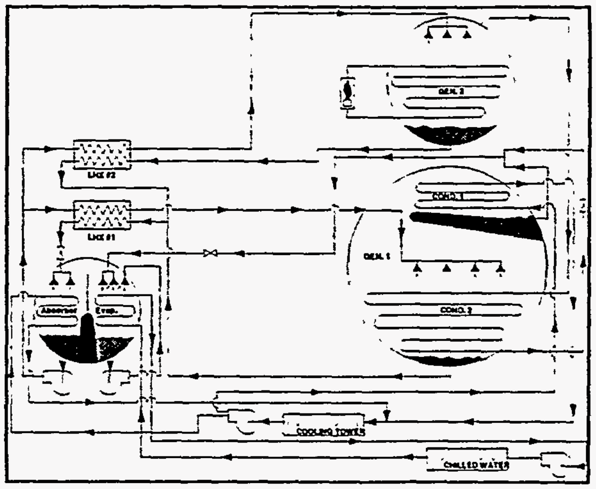

Figure 6. Double-Effect Lithium Bromide/Water Chiller Design

Double-effect absorption chillers have COPs of approximately 1.0-1.2 out of an ideal 2.0, again because of second law thermodynamic losses.

Although the double-effect machines are more efficient than single-effect machines, they have a higher initial manufacturing cost related to special materials consideration because of increased corrosion rates (higher operating temperatures than single-effect machines), larger heat exchanger surface areas, more complicated control systems, and the related increased manufacturing costs.

Triple-Effect Cycle

The triple-effect cycles are the next logical improvement over the double-effect. Although the United States and others are actively conducting research in this area, currently, there are no triple-effect absorption chillers manufactured in the world. Previous work has shown that there are theoretically a large number of cycles that fall into the category of "triple-efficiency" [9, 10, 11, 12, 13,14]. A basic three-condenser-three-generator triple-effect cycle was patented by Oouchi et. al. in 1985 (a pressure versus temperature representation is shown in Figure 7). An alternate triple-effect cycle, the double-

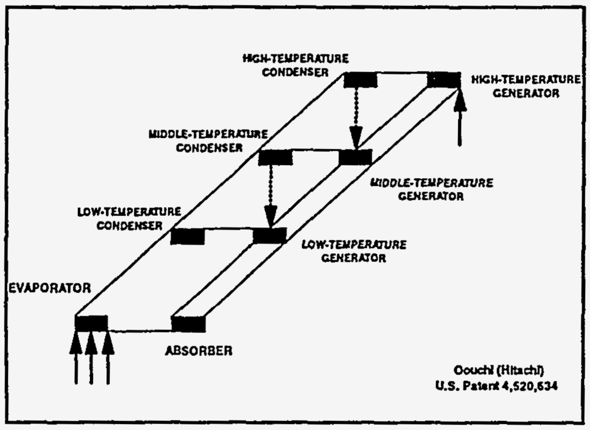

Figure 7. Triple-Effect Lithium Bromide/Water Absorption Cycle Represented on a Pressure versus Temperature Diagram (Oouchi, et al patent)

condenser coupled (DCC) cycle, was patented by DeVault and Biermann in 1993 (a pressure versus temperature representation is shown in Figure 8). An absorption chiller that uses this cycle could look like the schematic in Figure 9. LiBr solution is used as the absorbent and H_2O as the refrigerant. The cycle can be described as follows: a strong (refrigerant rich) LiBr/H_2O solution is pumped from an absorber to low, medium, and high temperature generators (in series). In each generator some of the H_2O refrigerant is boiled off and leaves as hot vapor. The refrigerant vapor from the high and medium temperature generators is condensed and this heat is used to provide the heat input to the next lower temperature generator. The refrigerant from all three condensers flows to an evaporator where it absorbs more heat. The refrigerant evaporates and the cold vapor is returned to the absorber. In the absorber, the LiBr solution (refrigerant weak) that is returned from

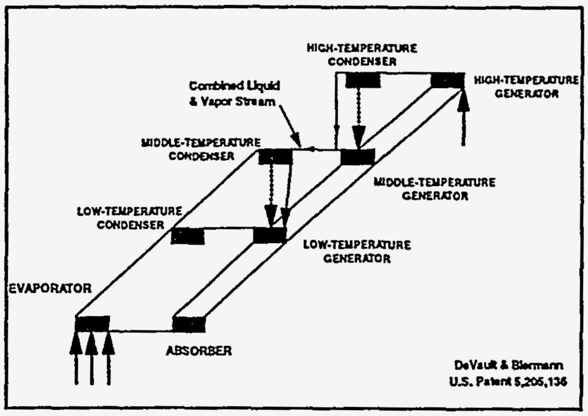

Figure 8. Alternate Triple-Effect Lithium Bromide/Water Absorption Cycle Represented on a Pressure versus Temperature Diagram (DeVault and Biermann patent)

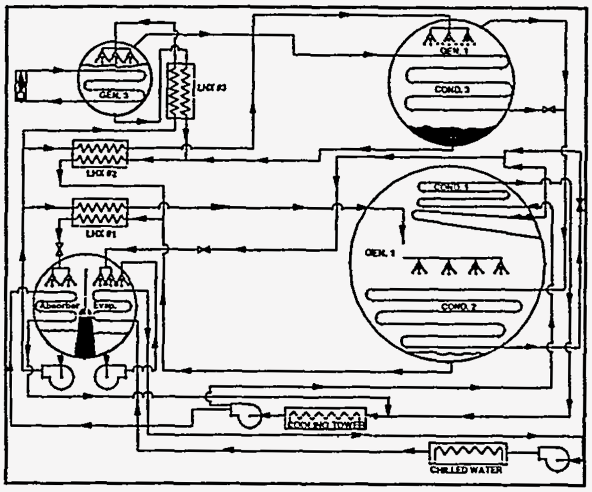

Figure 9. Triple-Effect Lithium Bromide/Water Absorption Chiller Design

the three generators reabsorbs the refrigerant. This now refrigerant strong solution is then pumped to the three generators where it repeats the cycle.

In the triple-effect chiller, three units of refrigerant vapor recovery are available for only one unit of heat input. However, because of second law thermodynamic losses, coefficients of performance have been calculated from 1.5 to 2.0 (depending on size of heat exchangers and type of cycle used) out of an ideal 3.0.

Predicted initial manufacturing cost of the triple-effect machine is somewhat higher than that of the double-effect machine. These higher costs are related to increased corrosion rates and more expensive materials of construction (higher operating temperatures than double-effect machines), larger heat exchanger surface areas (in some cases), higher pressures, more complicated control systems, and the related increased manufacturing costs.

The United States Department of Energy through its Buildings and Equipment Technology Program has partnered with York International to conduct triple-effect absorption chiller research. The "large commercial chiller program," involves research, development and evaluation of multiple triple-effect designs. The stated goal of the program is to produce a triple-effect chiller that improves cooling efficiency by 30 to 50 percent, compared with double-effect absorption chillers currently on the market. In a cost-shared subcontract with York International, several cycle possibilities for $LiBr/H_2O$ triple-effect absorption chillers have been evaluated. The DCC cycle is currently the base cycle being investigated by York International under this project. The primary objective of this project is to build fully functional hardware to demonstrate a practical triple-effect chiller for commercial air conditioning applications. The design goal for the prototype is to achieve 400 tons of cooling capacity. The final goal is a U.S. manufactured triple-effect absorption chiller.

Gas Cooling and the Environment

The heating, ventilating, and air conditioning (HVAC) industry is undergoing fundamental change. The single most significant driver for this change is global environmental policy . The Montreal Protocol saw to the end of CFC production within the industrialized world in December, 1995. In the year 2030 all HCFC production will globally cease. The Clean Air Act Amendment of 1990 regulated CFC emissions in the U.S. and also regulated SO_2 and NO_x emissions in "non-attainment" areas. The Energy Policy Act of 1992 requires that states establish electric integrated resource plans and requires an examination of gas integrated resource plans. Federal facilities are also required to reduce site energy consumption by 30% in the year 2005. President Clinton's Executive Order of March 8, 1994 contains an effort to meet CO_2 reduction targets necessary for compliance with the Rio Accords. All of these legislative activities are focused on pushing the nation toward energy efficient technologies that reduce harmful emissions. [15]

The contribution that current and future gas cooling technologies can make to buildings of today and tomorrow, in light of the preceding policies is substantial. A 1000-ton absorption natural gas fired chiller replacing a 1000-ton electric centrifugal cooling system utilizing power from a new coal-fired power plant will reduce emissions of NO_x from 4,077 lbs/year to 1,091 lbs/year, SO_2 from 4,077 lbs/year to 7 lbs/year, CO_2 from 1,399,737 lbs/year to 1,254,545 lbs/year and Total Particulate Solids from 3,397 lbs/year to 22 lbs/year [16].

Natural gas powered air-conditioning equipment also offers many advantages to the environment in the CFC and HCFC arena. Absorption units do not use CFCs or HCFCs as refrigerants. When comparing the direct (chemical) emissions of an absorption chiller to those of a vapor compression or engine-driven chiller that uses CFC or HCFC refrigerants, clearly absorption is the environmentally friendly technology. However, when making a comparison of indirect (energy) emissions over the end-use service life of the product, this comparison requires more analysis.

Absorption and Global Warming Impacts

Recently the debate over the potential impacts of ozone depletion, global warming and other environmental upsets has been widely reported in the national news media. Regarding the chemical emissions that are purported to cause environmental damage, scientists are now applying more rigorous techniques to compare the impact of competing technologies. Today's sophisticated technology comparisons use more of a "life cycle" or "systems" approach. Scientists are now considering the indirect effects of employing a specific technology, in addition to the standard comparison of direct chemical emissions. For example, a comparison of an electric powered window air conditioner and a gas-fired heat pump would look at the CO_2 equivalent loading from the power generation, A/C operation, refrigerant leakage, unit disposal, and finally removal of the chemicals from the atmosphere through natural processes (photodecomposition, interaction with oceans). This systems approach yields more thought provoking comparisons.

A report published by the Oak Ridge National Laboratory in 1994 [17], demonstrates comparisons of currently available technologies based on CO_2 equivalent loading in the atmosphere. All CFCs and HCFCs are assigned a multiplication factor to represent equivalent emissions as compared to CO_2. This report, titled the Alternative Fluorocarbons Environmental Acceptability Study (AFEAS), compares the global warming potential (GWP) for numerous CFC/HCFC refrigerants to the GWP for alternative refrigerants. However, the AFEAS report goes further and analyzes the global warming impact from a systems perspective and introduces a Total Equivalent Warming Impact (TEWI). The TEWI accounts for the atmospheric impact of a particular refrigerant in a specific application throughout the life of the device (including power production) and its associated decomposition. The results of the ORNL study and follow-on work will help to shape the debate regarding the merits of environmentally benign technologies.

Summary

Absorption chillers do not use CFCs or HCFCs, and they have reduced chemical emissions compared to equivalent vapor compression systems. As advanced absorption technologies are developed, absorption chillers will achieve efficiencies comparable to currently available vapor compression machines. The triple-effect chiller and other DOE-sponsored research will provide an opportunity for the United States to improve energy efficiency and to capture a significant share of an emerging global market. The ground-breaking work conducted at Oak Ridge National Laboratory in developing the TEWI model provides a scientific basis to frame the debate surrounding global warming potentials.

Additionally, the U. S. Department of Energy (DOE) is embracing the recognition of the environmental impacts of the power generation part of the equation. The DOE is currently sponsoring R&D in many areas of alternative power generation technology as well as technologies that reduce the direct impact of chemical emissions. Environmental stewardship has been recognized as one of the compelling reasons for continued government sponsorship of energy R&D [18]. It will be important for the U.S. to continue its leadership role in preserving our atmosphere. Through research and cooperation, the U.S. can lead the world in the fight to save the environment for future generations.

Acronyms

AFEAS	Alternative Fluorocarbons Environmental Acceptability Study
CFC	Chlorofluorocarbons
COP	Coefficient of Performance = Refrigeration Effect/Net Heat Input
CO_2	Carbon Dioxide
DCC	Double-Condenser Coupled
DOE	Department of Energy
HCFC	Hydrochlorofluorocarbons
Hg	Mercury
H_2O	Water
LiBr	Lithium Bromide
NO_x	Oxides of Nitrogen
ORNL	Oak Ridge National Laboratory
PTX	Pressure, Temperature, Concentration
R&D	Research and Development
SO_2	Sulfur Dioxide
TEWI	Total Equivalent Warming Impact

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