ABSORPTION TECHNOLOGY AS A SUSTAINABLE ENERGY SOLUTION IN THE UNITED STATES

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ABSTRACT

In the recent couple of years, there has been a significant drive towards sustainability in the U.S., fueled in large part by a greater awareness of the threats posed by global warming and to some extent by the need for energy independence. Research institutions and manufacturers are recognizing the role absorption can play in this endeavor and are taking steps towards adapting the technology to boundary conditions imposed by reduced environmental impact, primarily by providing energy-conserving solutions in the area of space and process cooling and heating. These include the coupling with distributed power generation devices such gas-fired engines and microturbines, and other low-availability sources such as process waste and solar heat, to yield integrated energy or polygeneration systems. This seminar attempts to capture the more significant of these efforts, in particular those that are making in-roads into the commercial arena. Recent developments on the research front and future trends will also be discussed.

INTRODUCTION - ABSORPTION MARKETS

In recent years, U.S. markets for absorption and heat-operated equipment have generally been down in sales. Some of the major U.S. HVAC manufacturers no longer produce in the U.S., teaming up with overseas manufacturers to retain a position in the shrinking market albeit with minimal technical collaboration. These companies, e.g. Carrier and Johnson Controls (York), continue to manufacture for an overseas market. Trane is the only company that still manufactures out of the U.S.

New development in stand-alone (traditionally applied) cooling and/or heating units is coming from manufacturers in India and China, e.g. Thermax and Broad. This is facilitated by rapid prototyping via in-line testing (sometimes factory-testing merged with development testing), driven by a strong demand for process as opposed to comfort cooling from refineries and other chemical plants. These manufacturers have evolved to be equipped for quick customization to meet this demand.

Currently, in addition to the low sales volumes, the U.S. seems to be witnessing a decline in the number of installations / units in operation. This is the feedback from specialized service organizations that periodically perform analyses and maintenance on absorption chillers (Rockenfeller, 2007). Relative to these companies, the original equipment manufacturers only have about 15% of the service market. This is because of the lower cost and faster turnaround offered by the independent service organizations. Chemistry analyses of single-effect chillers (generally steady due to the intrinsic robustness), e.g. those used for process cooling in places such as Houston, TX (oil refineries), indicate that the operating hours are down. Estimates put these at about 25% of capacity. For the double-effect direct-fired chillers, this can be attributed to soaring natural gas prices. These have climbed to over $7/MMBtu from $2/MMBtu in less than 6 years, when operating capacity was already down to 50%. In the same period, electricity prices have only risen from about $0.08 to $0.10 per kWh (as high as $0.13/kWh in some areas). At $0.10/kWh, only about half the utilities have any incentives in place to promote absorption cooling, resulting in a meager 2-5% area (cooling market) coverage nationwide. In short, there is little opportunity for gas cooling at current energy prices in the U.S.

On the unitary side, in addition to the high gas prices, manufacturers have suffered from a diminishing distribution capability and an unfavorable euro vs. dollar relationship (for selling in the U.S. by European manufacturers). One manufacturer - Robur - has returned to Italy, to focus on the European market, as a result of these factors. Thus, unitary gas cooling in the U.S. has a pessimistic outlook as well.

TECHNOLOGY DEVELOPMENTS ON THE CHILLER (LARGE-TONNAGE) SIDE

In spite of the discouraging market conditions, significant developments have taken place in the absorption field. These have mostly been in the area of polygeneration or CHP - combined cooling, heating and power. This is the result of a growing awareness of the need for energy conservation and associated opportunities on the part of manufacturers. A number of these efforts have been sponsored and supported by the U.S. Government: the Department of Energy and the Oak Ridge National Laboratory.

Given the state-of-the-art and maturity of absorption technology, it became quickly evident that the key to the success of polygeneration was optimized integration. The Government adopted this approach in the earlier part of this decade, when promoting polygeneration through various R&D programs. Some private sector companies took advantage of these programs and developed commercializable components and/or systems.

In 2001-2002, Trane designed and tested a single-effect water-lithium bromide absorption chiller for low-grade waste-heat utilization (Patnaik, 2004). The nominal capacity of the chiller was 90 tons, and it was driven by water intended to be heated by both the exhaust stream and jacket water of a 400-kW gas engine (Fig. 1).

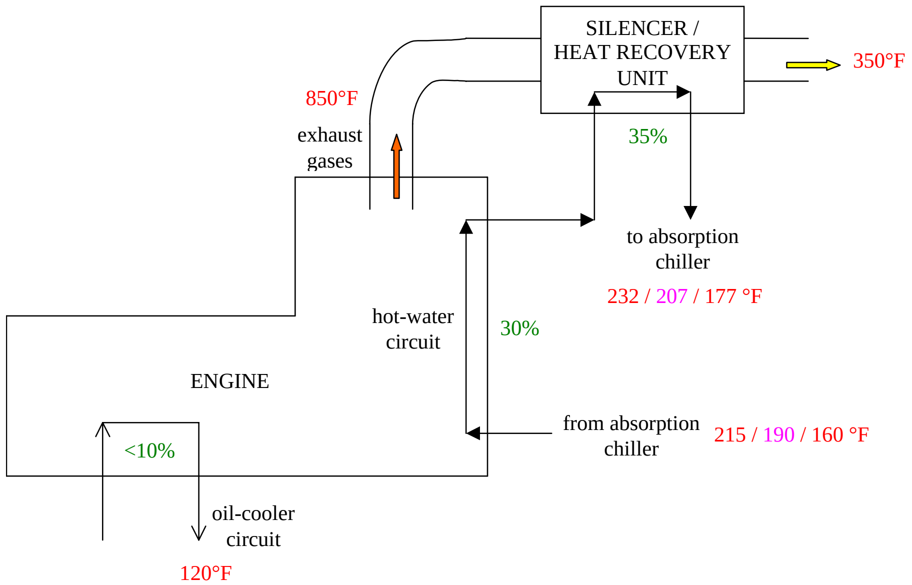

Figure 1: Engine Operating Conditions Trane BCHP chiller.

Lab performance of the stand-alone chiller matched expectations, with a COP of 0.75 at full load and standard ARI rating conditions. Areas in the need of improvement were eliminator and sump design, for better control of the cross-migration of salt and refrigerant (salt carryover and refrigerant slinging) between the generator and condenser and consistent attainment of design solution flows, respectively.

This was a cost-optimized design, substantiating the promise of thermally-activated equipment integrated with distributed power generation sources to meet building energy needs holistically, with a single package. However, other priorities, primarily relating to refrigerant phase-out, and the downbeat market conditions, displaced any further development and commercialization. The proof-of-concept chiller is shown with dimensions in Fig. 2.

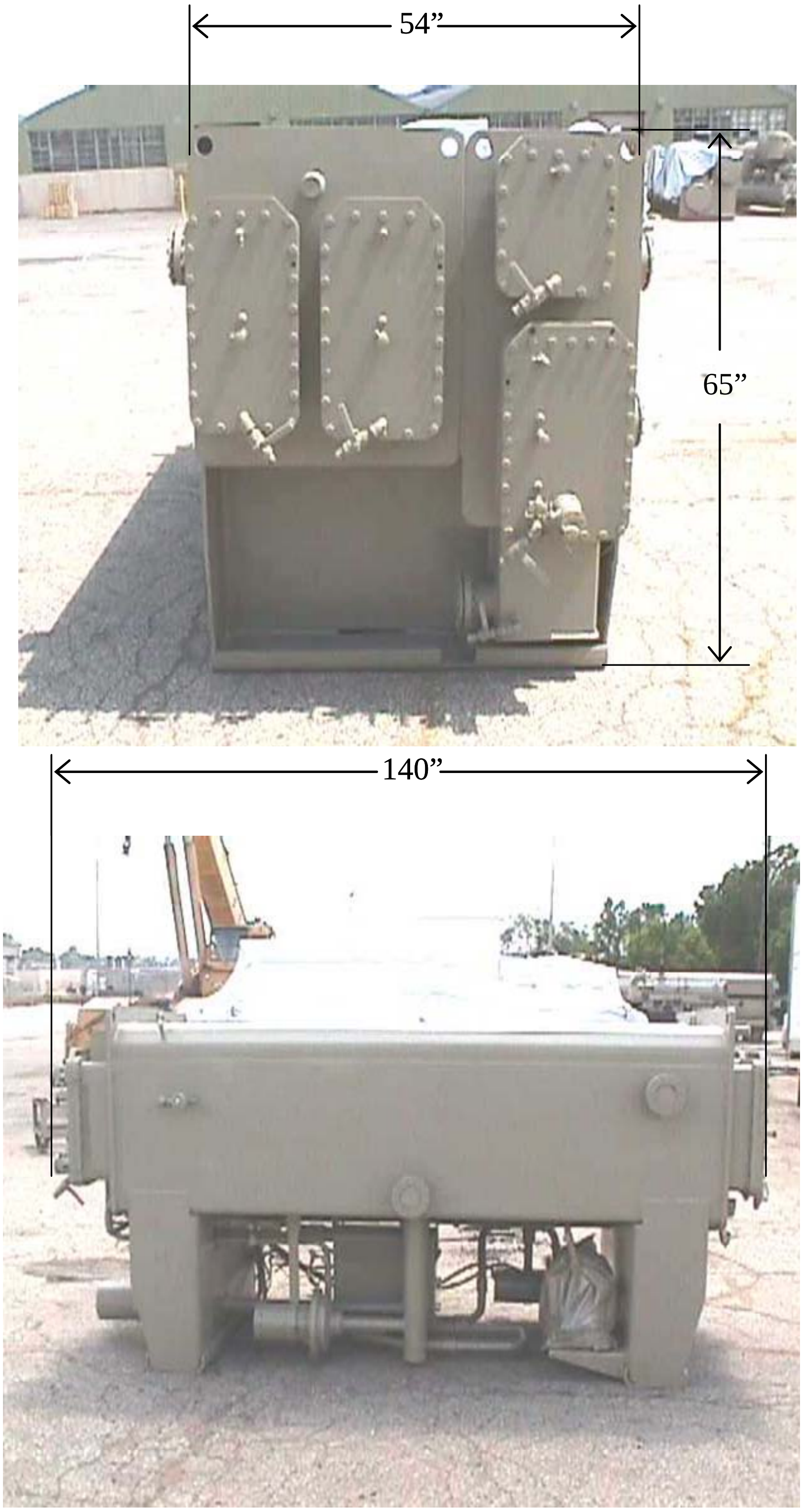

Figure 2: Post-testing Trane BCHP chiller, prior to shipping for system integration.

United Technologies (UTC) has invested further in R&D and actually commercialized an integrated system. This system combines a battery of microturbines with a single absorption chiller and is known as PureComfort. The absorption chiller is a commercially available double-effect, direct-fired chiller, with the generator modified to have additional heat transfer surface area (smoke tubes) in the space originally occupied by the burner/combustor. UTC has adopted a modular configuration approach, with their Phase 1 system consisting of 4 60-kW microturbines the exhaust from which is directly plumbed to the absorption chiller (Fig. 3). Under standard operating conditions, they measured 229 kW net power and 161 RT cooling from their lab system, which translates to over 90% polygeneration efficiency.

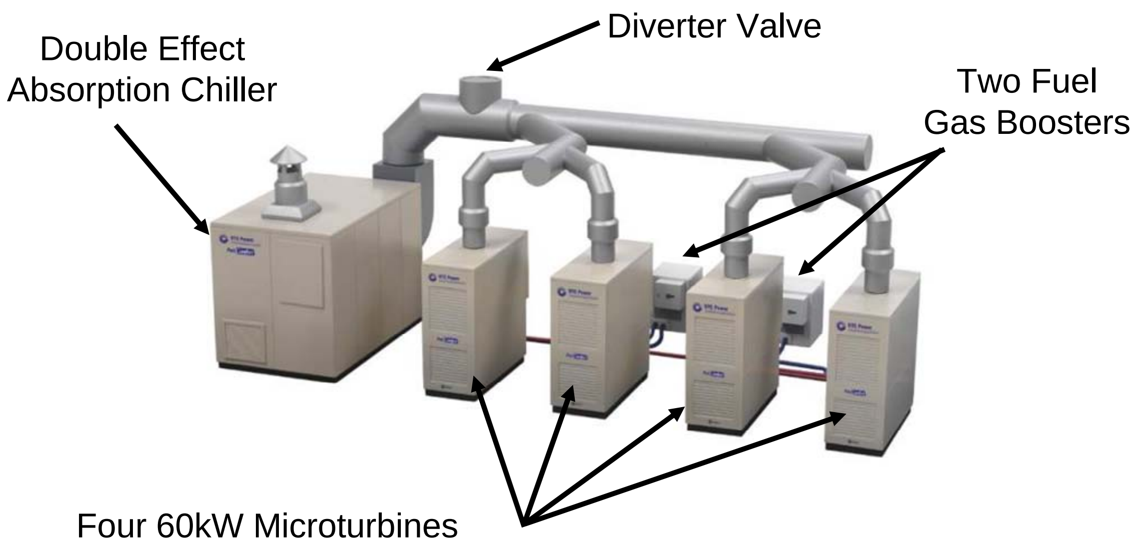

Figure 3: PureComfort 240-kW CHP system (Courtesy: Tim Wagner, UTRC).

The next phase of development focused on chiller improvements, the most noteworthy of these being the replacement of the smoke tubes with liquid tubes (water-LiBr on the inside, flue gas on the outside) in the generator. This is resulted in reduced gas-side pressure loss (back pressure) and consequently higher CHP performance. The controls were also improved for robustness during transient conditions. Thus, constant heating output could be achieved even during step changes in microturbine electrical load. The above developments allowed for product expansion (varying number of microturbines), without impacting the system efficiency significantly.

UTC continues to push polygeneration into the mainstream. They have now moved their efforts to cooling *and* heating coming from the absorption chiller, and coupling with engines, in the range 300-500 kW (Wagner, 2007). The major developments in this phase include optimally positioned control valves and extra sump volume (Fig. 4). The engine-coupled product has an exhaust gas -fired version that runs off 1050°F and a hot water -fired version that runs off 190°F. There is also a hybrid version in technology phase (Fig. 5), where the heat source for the low-stage generator is split between the engine water and the high-stage generator vapor. The objective with the simultaneous cooling and heating product is to provide all-year-round polygeneration. However, the market for such products is still soft. At this point, the microturbines-coupled product enjoys greater acceptance than the engine-coupled product.

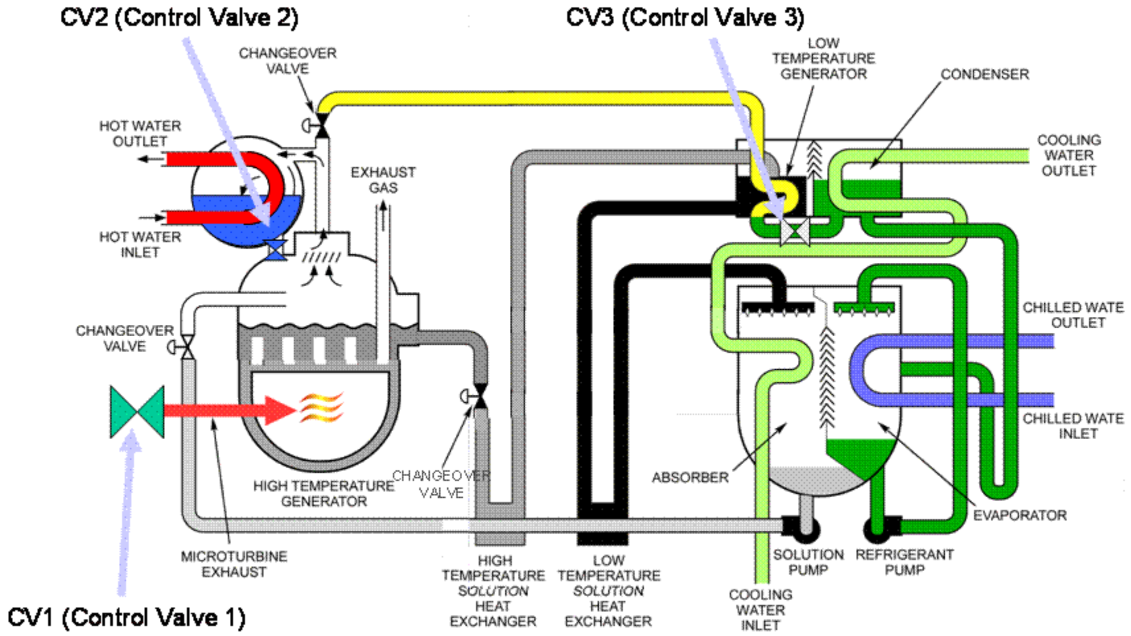

Figure 4: CHP technology with simultaneous cooling and heating (Courtesy: Tim Wagner, UTRC).

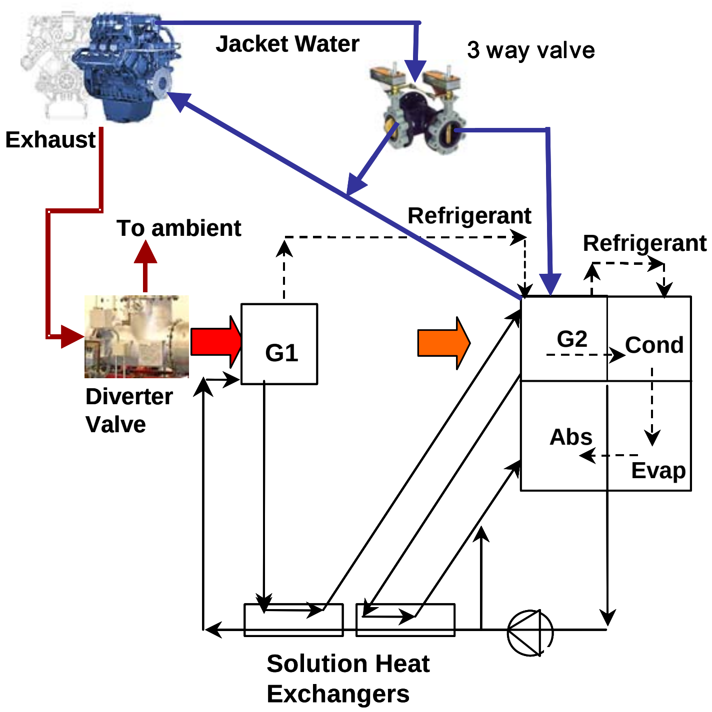

Figure 5: Hybrid engine CHP technology (Courtesy: Tim Wagner, UTRC).

The state of California has a number of successful installations of polygeneration systems. These include a UTC microturbines-based packaged system at the Ronald Reagan Library in suburban Los Angeles (Wagner, 2007) and a Tecogen/Tecochill engine-based system at the Motion Picture and Television Fund hospital in the capital city of Sacramento (Martini, 2007). The engine has a capacity of 75 kW and operates electric-gas hybrid machinery (3 electric, 2 gas chillers) for fuel cost flexibility. High emissions control is achieved using a catalytic converter and an O_2 sensor (strict control of A/F mixture to run slightly rich). The polygeneration system yields $30,000 savings/year including maintenance costs.

York / Johnson Controls (JCI) is also involved in developing high-efficiency integrated energy systems. They have installed two types of polygeneration at the Los Angeles International Airport (Spanswick, 2007). These are a turbo-absorption chiller, consisting of steam-driven centrifugal and single-effect absorption chillers in series, and a condensing-turbine steam chiller, all integrated including the heat-recovery steam generator. The system is thermally base-loaded, meeting the full heating and cooling loads, and even produces excess electricity, which is put back on the grid. It operates at 25% electrical efficiency and 66% overall or polygeneration efficiency. Other installations include the LA County building, UCLA and LAC-USC hospital. The two types of chiller systems are similar in cost and efficiency, although, in practice, the latter tends to be higher for the condensing-turbine chiller. Additionally, space constraints do not favor the turbo-absorption system, owing to the greater number of components. Hence, in general, JCI is moving from turbo-absorption toward condensing-turbine systems. They are also exploring steam turbines with gas turbine-based polygeneration, where high-pressure steam is generated from the waste heat.

A key application consideration for polygeneration projects is the thermal-to-electric load matching (Foley, 2007). A recommended strategy is to base-load both, giving priority to thermal load, i.e. high load factors. The T/E ratio is about constant down to 90% part load; beyond that, it increases. Another operating strategy, coming from the very high natural gas prices seen in recent years, is to shut off the polygeneration system at night and buy the electricity, i.e. switch to the grid during the night when electric rates are lower (Wagner, 2006).

Although polygeneration systems are generally reliable, there are some to hurdles to their proliferation. According to customers such as utilities (Con Edison, 2006), if there *is* a problem and parts are needed, response can be slow from some manufacturers. In addition, for some non-U.S. manufacturers selling in the U.S., it becomes especially difficult, given the minimal gathering of the voice of the customer prior to innovation endeavors, and in some instances, unfamiliarity with conducting business in a different environment (Sweetser, 2007).

Nevertheless, there have been some impressive developments and installations of absorption-based technologies by non-U.S. companies such as Thermax and Broad, e.g. an engine-driven solar hybrid (with burner) chiller (Pathakji, 2007). The lead time for such systems is about 18 weeks and they are delivered on site pre-packaged. In the context of renewable energy, however, an interesting argument emerges that is not in favor of absorption. If electricity and heating come from renewable sources, the choice of technology would almost entirely be determined by first cost.

TECHNOLOGY DEVELOPMENTS ON THE UNITARY/RESIDENTIAL SIDE

Absorption heat pumps offer the benefits of high efficiency and high capacity at low ambients, relative to their electric counterparts. Rocky Research makes units up to 10 tons (120,000 BTU/h) for niche markets (defined as under 1000 units per year), e.g. areas with higher heating hours such as the northeastern US, hydronic heating in Europe which enjoys easier integration due to the available infrastructure. These are dual-temperature units, providing simultaneous heating and cooling, with a heating COP of 1.45 at 47°F ambient, compared to 0.90 for the typical condensing furnace. At low ambients (-20°F), these efficiencies drop substantially but the units still provide heating, unlike electric heat pumps. Cooling COPs are about 0.70.

Other applications include using waste heat from engines, small turbines and fuel cells. In the case of turbines, there is some concern over the back pressure imposed by the heat exchange equipment. This tends to lower the electrical efficiency of the turbine. Pool heating and dehumidification are also a common application, especially with the dual-temperature units.

Most recent technology developments have centered around energy efficiency improvements. The 0.70 cooling COPs, going up to a seasonal efficiency of 0.85, were achieved with enhanced and easily wettable heat transfer surfaces and variable-speed drives on the condenser fan motor, burner and solution pump (Rockenfeller, 2007). The electric power usage is only 1 kW (tunable to 750 W) for 5 tons, i.e. << SEER.

Figure 6: Ammonia-Water 5RT Gas Fired Air Conditioner (Courtesy: Uwe Rockenfeller, Rocky Research).

The high-efficiency products employ ammonia-water technology with generator-absorber internal heat exchange (GAX). Lately, activity in this area has been supported more by private industry (GE engines) than by the U.S. Dept. of Energy. This is for landfill gas type applications, pool heating and process cooling. The GAX cycle is operational down to 5°F, with the combined heat of rejection from the condenser and the absorber being a relatively weak function of the ambient temperature. This makes the absorption heat pump a much more attractive heating technology than electric heat pumps with electric resistance heat for low ambients.

The other company in this sector, Robur, regularly exhibits their Italian-made 5-ton ammonia-water absorption AC / heat pump at the AHR/ASHRAE winter exposition. Their U.S. presence rests on the presence of a niche market for GAX-based heat pumps. Efficiencies of this product are still low, with cooling COP =0.64 and heating COP = 1.26. Robur also has a waste-heat -driven version of their product, with supplemental gas-firing capability, and are teaming up with EchoGen to produce 15-100 kW polygeneration systems.

Unitary product development has thus focused on tapping into the uniqueness of the absorption cycle for large amounts of heat that are ordinarily rejected, not so much for comfort cooling. At the same time, the sub-critical product density has had the tendency to drive the smaller manufacturers to becoming OEM service/distribution providers for the niche markets.

TECHNOLOGY DEVELOPMENTS ON THE INDUSTRIAL/PROCESS SIDE

Ammonia-water equipment is not quite on its way to obsolescence in the U.S. A small company out of Annapolis, Maryland, has made great strides in developing such equipment for the industrial or process cooling sector. Energy Concepts has designed chillers utilizing cycles ranging from simple through advanced GAX, and gone beyond to integrate these with power and other energy systems (Erickson, 2007). For example, 25°F refrigeration for a melon storage warehouse is obtained from Energy Concepts' 160-ton "Thermochiller" running off waste heat from an 830 kW gas-fired reciprocating engine. Both exhaust and jacket water heat are used. The unit has only an 8 ft by 8 ft footprint and weighs 9000 pounds (Fig. 7).

Figure 7: 160 ton Thermochiller (Courtesy: Don Erickson, Energy Concepts).

An unusually interesting installation of the same product is a 16-ton Thermochiller at an ice museum/hotel in Aurora, Alaska (Fig. 8). All the interior of the hotel, including the furniture, is sculpted from ice (Fig. 9), and the chiller keeps the structures from melting. The dimensions (W×D×H) of this unit are: 4×4×6 [ft] (1.2×1.2×1.8 [m]).

Figure 8: 16 ton Thermochiller installed at Aurora ice hotel (Courtesy: Don Erickson, Energy Concepts).

Figure 9: Ice hotel interior (Courtesy: Don Erickson, Energy Concepts).

Other Energy Concepts installations include “Thermosorbers”, ranging from 10 to 100 tons, for poultry processors. These simultaneously yield heating (heat pumped hot water), e.g. 100 tons of cooling (40ºF chilled water) and 3.2 MBH of heating (136ºF hot water) from 2 MBH of steam. (This particular installation saves 30% of heating and 80% of chilling energy, with automated, unattended operation, 20 hours a day, 5 days a week. Typical payback is less than 2 years.) The Thermosorber uses a single-effect cycle, with the heated water flowing in series through the condenser first and then the absorber.

Another noteworthy installation is the 60 ton “Helichiller” system at Cochise College, Arizona, which provides air conditioning from 210°F solar heat at 0.75 COP. The system includes a 7500-gallon hot water storage tank.

Figure 10: 60 ton solar-fired Helichiller (above) with storage tank (below) (Courtesy: Don Erickson, Energy Concepts).

Energy Concepts has also devoted resources to enhancing/enabling power cycles. For gas turbines, they have developed inlet air cooling devices that increase the density of the air, thereby increasing the throughput (mass flow rate) and ultimately the power generated. These devices employ the dual-function absorption cycle (Erickson et al., 2004), wherein the waste heat from the turbine combustion process drives a single-effect ammonia-water absorption chiller, which in turn cools the inlet air to the turbine, giving the desired power boost. Additional power can be generated via an expander installed between the heat recovery vapor generator and the absorber, as shown in Fig. 11. Other manufacturers have supplied more conventional absorption chillers, driven by steam or hot water, for turbine inlet air cooling.

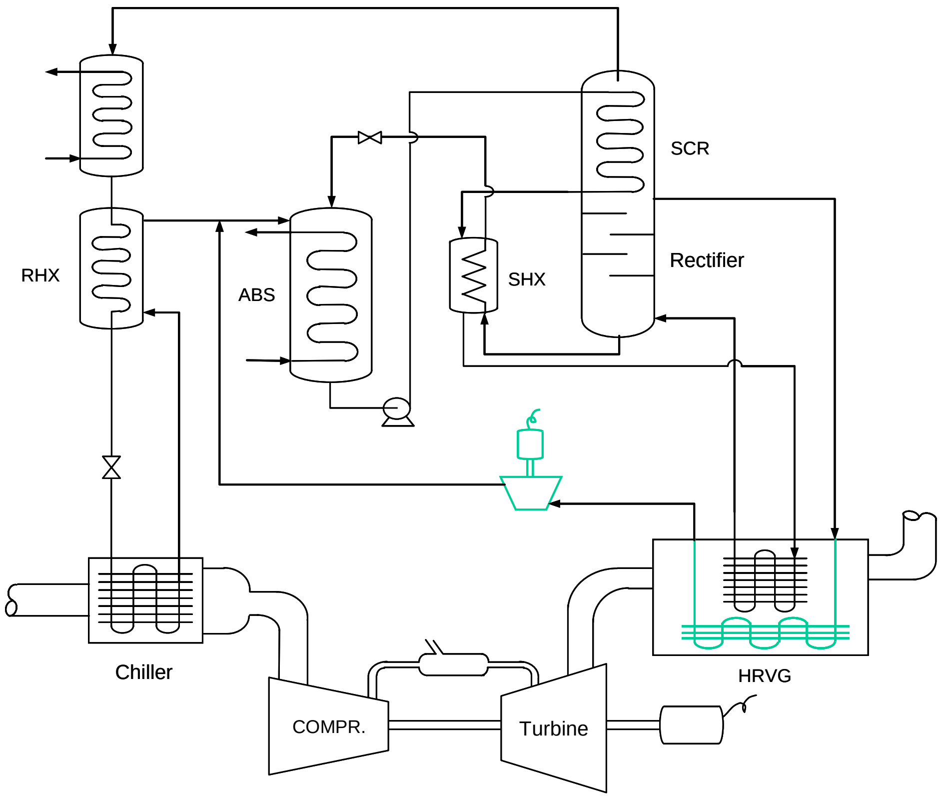

Figure 11: Dual function absorption cycle for power generation boost (Courtesy: G. Anand, Energy Concepts).

Some characteristics driving the design of modern ammonia-water absorption equipment are: compactness / small footprint, light weight, low ammonia charge (for safety), efficiency, low driving (source) temperature, low cost, air cooling option, chilled temperatures down to -50°F, heat pumping option, temperature glide utilization (counterflow heat and mass exchangers) and robustness (reliability). Safety is of particular interest, as ammonia does not have widespread acceptance in the U.S. owing to its toxicity and mild flammability. This is another significant factor why such equipment has not become more prevalent in this country.

INDUSTRY-WIDE EFFORTS

On the renewable source front, very limited activity has occurred to package solar-fired absorption systems. Solargenix has been developing solar thermal technologies. They are taking their cue from the U.S. auto industry of the 80's and avoiding the short-sightedness that could cause the U.S. HVAC industry to be left behind (Guiney, 2006). Again, overseas manufacturers are rushing in to secure jobs starting from demos, e.g. Yazaki with a commercially available 20-ton absorption unit and Chinese manufacturers with 1/2-5 ton units. There are also some solar demos with single- and double-effect installations up to 50 tons (overseas-made, e.g. Broad).

The projects typically use a compound parabolic collector (CPC) utilizing non-imaging optics to focus sunlight onto a high-efficiency absorber tube. The CPC is a flat plate, non-evacuated single glazed collector. The dimensions of each collector are 82.44"x41.77"x3.31". The chillers can be driven with the heat from these collectors, backed up by natural gas boilers. The solar field for a 30-ton system consists of approximately 180 collectors, shown in Fig. 12.

Figure 12: Austin Energy solar collector field for polygeneration (Courtesy: Solargenix).

Various U.S. universities are continuing to engage in absorption-related research. These include the University of Maryland, College Park, and George Institute of Technology, Atlanta. Maryland recently presented some work on an *application-based*, compact, air-cooled water-LiBr chiller, intended for higher evaporator temps (Radermacher, 2007). Georgia Tech has been focusing on the fundamental absorption (transport) processes, developing advanced techniques for the visualization and modeling of the hydrodynamics, heat and mass transfer in the film and droplet regimes (Killion and Garimella, 2004).

In recent years, ASHRAE has been very active in promoting sustainability in the HVAC industry. The ASHRAE GreenGuide is one such effort, which offers engineers, architects, consultants, contractors etc. techniques and tips on sustainable design practices, both at the equipment and building level. A section in the chapter on energy conversion systems and a GreenTip are dedicated to CHP (Patnaik, 2007).

There is also an energetic debate going on at the ASHRAE bi-annual meetings on exergy or availability and the role it plays in sustainable design. The take-away message is to match the *quality* or grade – and not just quantity - of the source energy to the end use. This directly promotes the adoption of absorption, specifically low-grade waste-heat or solar fired, i.e. polygeneration systems.

The exergy approach, of course, comes at a capital- or first-cost premium. However, over the life cycle of the equipment, this cost is recovered and money is saved, with the added benefit of lower environmental impact. In addition, the true cost is not captured by the first cost, from a material and energy resource depletion and long-term environmental repair standpoint (Hawken et al., 1999).

CONCLUSIONS

Given the recent interest in the environmental impact of HVAC equipment (direct and indirect) and the dramatic rise in energy costs (gas and electricity), absorption technology is seeing a slump in the U.S. but emerging in niche applications that integrate multiple energy systems. This is in recognition of the fact that stand-alone, (direct-fired) absorption would contribute more to CO_2 production than vapor-compression owing to lower cycle efficiencies tied back to the energy source. In separate consideration, recent concerns over power reliability and quality have led to an interest in distributed power generation devices such as engines, microturbines and steam turbines. Manufacturers are coupling absorption equipment with these devices via the combustion waste heat, to push overall fuel utilization efficiencies to over 80%.

The other area of current application of absorption is simultaneous heating and cooling. This can be via direct diversion of combustion heat or, particularly for unitary and process jobs, via heat pumping. The ammonia-water cycle lends itself well to the latter, with GAX heat pump efficiencies over 50% higher than conventional boilers/furnaces and a better response to low ambients than electric heat pumps (lower balance points, less supplemental heat).

In spite of the obvious benefits, however, absorption units these days are not quite mass-produced in any category, in an extremely first-cost conscious society. Still, if the source of energy is fossil-fuel based, combined cooling, heating & power or polygeneration systems are providing an environment-friendly and economically justifiable (over the life) energy solution. If the source of energy is renewable, such as solar, absorption might be limited to niche applications, particularly in remote areas, where the electrical infrastructure is inadequate.

Closing with a more thermodynamic and hence philosophical perspective, today, with fossil fuels, we are using high-quality/exergy sources for relatively low-quality (temperature) applications, which is wasteful from a 2nd-Law standpoint. We need technologies that will match the quality of the available energy to the end use or application, such as polygeneration.

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