feature article

Stirling renewal

Refrigerators and generators that use an alternative thermodynamic cycle are a green engineering hotbed.

By Gale Morrison, Associate Editor

In 1816, Scottish engineer and theologian Robert Stirling won a patent for an engine design that called for a volume of gas at a low temperature to be heated externally, and then forced into a greater volume and allowed to expand quickly. The energy of expansion in turn drives the recompression of the gas. The work of the cycle can drive motion, create electricity, or perform other tasks.

Or, as another engineer realized around 1873, one can use a proper coolant that absorbs heat at the compression stage and then that heat can be removed, via an exchanger, from a chamber. The removal will regulate the chamber's temperature at a desired low point. And so, Stirling cycle cooling created prototypical refrigerators.

Such is the stuff of every mechanical engineering undergraduate's thermodynamics course syllabus. Stirling's design still engenders excitement and loyalty among hobbyists and enthusiasts from Australia to South Africa to a large U.K. contingent to a California man who powers his canoe with a Stirling engine.

But Stirling's design wouldn't dictate the engines or the refrigerators of the 20th century. Internal combustion engines working with liquid petroleum fuels would take over, and the thermodynamic cycle noted by Stirling's Scottish contemporary, William Rankine, would gain acceptance for refrigeration because of the advent of chlorofluorocarbons like Freon and hydrofluorocarbons.

A meter in the foreground shows the temperature, 100°C, of the combustion chamber of Sunpower's Biowatt pelleted biomass generator.

Things are different in these last few months of the century, however. Innovation now means environmental benevolence and super efficiency with the power that is generated. Developers say that designs based on the Stirling cycle offer significant efficiencies, and Stirling-based refrigeration systems need no fluorocarbons.

Stirling coolers that incorporate the late 20th-century improvement of a free piston and use helium or molecular nitrogen, instead of CFCs or HFCs, are getting a very close look, in both contract and large corporate research and development. The large automakers, including DaimlerChrysler Corp., are said to be making the global rounds to find out more about Stirling compressors.

And Stirling engines are being investigated for distributed electric power generation. That's because many see more efficient generation right where the user wants it, as an alternative to building more fossil fuel-burning plants and then constructing miles and miles of grid lines for transmission.

A prominent name in current research and develop-ment of Stirling cycle refrigeration is David Berchowitz. Berchowitz is a South African-born engineer who has spent most of his career at two U.S. companies working with Stirling technology. At Sunpower Inc., in Athens, Ohio, Berchowitz worked with the patenter of free-piston Stirling systems, William Beale. Among Sunpower's achievements are a cryocooler and a home power generator that use the principles of the Stirling cycle.

By 1995, Berchowitz had decided to develop a solar-powered refrigerator system, using technology licensed by Sunpower, and founded his own company, Global Cooling, just down the road in Athens.

"It's the ultimate cycle," Berchowitz said of the Stirling system. The only problem he sees with it is that no one has designed a marketable system that satisfies manufacturers and consumers alike. "We believe that our unit is a practical example of this thermodynamic cycle," he added.

Global Cooling has produced 100 prototypes of a 100-W-capacity cooling system driven by a Stirling machine. They have been sold or loaned out around the world to companies, including major appliance original equipment manufacturers, Berchowitz said. The prototypes have generated enough income and interest to sustain Global

Cooling thus far.

The company is properly known as Global Cooling BV, with headquarters in the Netherlands, because of its Dutch government and industry backing. The Dutch have put a special emphasis on seeing that household refrigeration takes less power, as has the U.S. Department of Energy.

The U.S. agency has told manufacturers that the refrigerators produced in 2001 will have to use 30 percent less electricity than those on the market today. Its estimate is that this will save more than 222 trillion Btu of primary energy per year and, of course, reduce pollution.

Berchowitz runs the American arm of the company, Global Cooling Manufacturing Co. Besides the solar-powered refrigerator, which he sees finding a home in the developing world where there is often no cooling for food and medicine, a second project is also under way. With the help of Jarlath McEntee, a Stirling designer and analysis software developer based in Castine, Maine, Global Cooling intends to make and market a portable refrigerator. Because a Stirling machine needs fewer parts for cooling, these refrigerators can be as small as a few liters, which the Rankine design cannot. A Stirling refrigerator would weigh about one-third as much as an equivalent Rankine system.

Berchowitz said that free-piston Stirling refrigeration has advantages over conventional Rankine refrigeration systems. Practically all current domestic refrigerators have a Rankine-cycle cooling system, driven by a motor-compressor. In a Stirling refrigerator, this system is replaced by a Stirling-cycle cooling system, driven by a free-piston Stirling machine. Current Rankine systems show a characteristic decrease in efficiency as the demand for cooling decreases, for instance, when the refrigerator is maintaining a cold condition, he says.

Free-piston Stirling coolers operate efficiently at all levels of demand because they can modulate their capacity to match any requirement. Berchowitz said they use no environmentally damaging fluorocarbons or hydrocarbons, which Rankine systems require. It was Greenpeace and Energie Holland NV that partly sponsored the 100 preproduction prototype Stirling coolers that have been made for testing purposes.

Global Cooling modified the 1997 world refrigeration record holder, a Bosch KDR 3700 364-liter refrigerator,

to incorporate its free-piston Stirling cooler instead of a conventional Rankine system. In-house testing revealed a 30 percent improvement in energy efficiency. The Stirling system consumed 110 kWh of electricity per year versus the Rankine's consumption of 138 kWh. In a statement on its website, Global Cooling said: "While the Bosch KDR 3700 does not represent an average refrigerator, the 30 percent improvement is a verifiable number, and it shall be used for a conservative estimate of expected energy savings. Compared to actual average home refrigerators, the Global Cooling Stirling system can be expected to improve energy efficiency by more than 70 percent."

A recent DOE estimate says that 1,954 GW hours of primary energy would be saved over a 30-year period if domestic refrigerator energy efficiency were improved by 30 percent. This equates to an annual energy saving of 65 GW hours, which would be equivalent to the output of a 7.4-MW power plant.

At least three major appliance manufacturers are currently sponsoring development work at Global Cooling.

Biomass to Electricity

It seems that just about every mechanical engineer who is involved with Stirling cycle systems has worked at Sunpower Inc. at one time or another. Berchowitz spent approximately 16 years there. The company produced its first commercial Stirling cycle cryocooler in 1994.

Sunpower's latest contender in the Stirling cycle system race is Biowatt, which is the trade name for a line of electric generators with a free-piston Stirling engine heated by burning biomass. Stirling enthusiasts are extremely excited about this new system. The generators will convert various biomass (wood, wood pellets, sawdust, chips, or biomass waste) to alternating electricity and useful heat. Sunpower's Stirling engine technology licensee is External Power LLC of Indianapolis.

Sunpower believes that Biowatt systems generating 500 W to 10 kW of electrical power will meet the need of electricity and heat in many residential, small commercial, and agricultural applications. The system converts 15 percent of the fuel energy to electricity; 70 percent of fuel energy is then available for heating water and spaces. It is this type of efficiency, coupled with the fact that transmission losses disappear because the system

is on site, that has the environmentally conscious more than intrigued. One of the significant benefits that Stirling cycle engines hold over an internal combustion counterpart is their quieter operation.

Sunpower currently has working prototypes of the system, and intends to demonstrate them in Amherst, Wis., next month at a renewable energy fair. It also plans to discuss them in great detail during a technical conference in Oakland, Calif., at the end of August. The target date for introduction of the first product, a unit generating 1 kW of electricity, is 2001.

The Biowatt burner includes a ceramic fire box and a fuel hopper with a fuel capacity of 24 hours. It accomplishes complete two-stage combustion with low emissions, according to Sunpower. The engine-alternator is said to require no maintenance because its gas bearings eliminate contact, friction, and wear. Its projected life is 40,000 hours with the integrated alternator producing load-following output at 50 Hz of 240 V or 60 Hz of 120 V.

The Biowatt generator is an example of what the power generation industry calls "distributed generation," an analogy to the computer science tenet of distributed computing. Deregulation among electricity providers could engender greater experimentation with these off-the-grid systems, and the Biowatt also moves toward the goal of reducing the fossil fuels burned to generate electricity.

Of course, sufficient combustible biomass could be hard to come by in an urban or coastal environment, but many see potential for rural and wooded areas, among other places. Sunpower points out that the Department of Energy's biomass research shows that even cities have biomass. Estimates show that New York City generates 10,000 tons of clean wood waste per day, enough to supply 150,000 1-kW units.

Because the system generates both electricity and heat, Sunpower calculates that the total cost of electricity over the generator's lifetime—even when buying a $100 cord of wood to fuel it—will be much lower than competing sources of electricity, including diesel and gasoline systems.

Sunpower also produces other kinds of free-piston machines. Its Stirling coolers reach the temperatures near absolute zero required by superconductors, and they produce profits that fund more R&D.

Car Air Conditioning

In Tel Aviv, Medis El, a spinoff from Israel Aircraft Industries, is working on prototype Stirling cycle reciprocating linear compressors that could be integrated for both appliance refrigeration and automotive climatization; that is, heating or cooling. IAI is the Israeli government-owned defense and aerospace company, which is fueled, as Medis El is, by engineering talent from across the diaspora, including the former Soviet Union.

A graphical representation of a portable, solar-powered Stirling cycle refrigerator that Global Cooling BV intends to license to an appliance OEM.

Medis El contends "major multinational companies" that develop refrigerators and car climate systems are already on board. Global Cooling and Sunpower make the same claim for themselves, but all three companies say they cannot divulge who their partners are, because of nondisclosure agreements and for other proprietary reasons.

Medis El's reciprocating linear compressor has just clearance seals instead of dynamic seals, which prevents wear. Like Sunpower and all free-piston Stirling compressors, Medis El uses air bearings on which the piston moves, so vibration and noise are reduced dramatically. Because a linear motor controls the piston's movement, it is precise and adjustable. A second Medis El patent has been allowed, which covers the displacer/expander component of the compressor.

Medis El currently is completing work on a prototype 65-W refrigeration unit. Using simulation software of this design, Medis El compared its reciprocating linear compressor model with a conventional Rankine cycle model. In a 400-liter standard home refrigerator with 260 W of cooling capacity, the Rankine system would require 290 W of input power, and the Medis El model 155 W. The coefficient of performance in the Rankine would be 0.9, where Medis El predicts 1.7.

The most beneficial comparison is in refrigerants: The Rankine requires freon or another fluorocarbon, and the Medis El Stirling refrigerator uses helium or molecular nitrogen. Further, Medis El says the power consumption to reach cool-down of its refrigerator is half that of the Rankine-based system. This comparison is based on one-third volume at -17°C and two-thirds volume at 4°C.

Medis El says that it has an agreement with a U.S.-based multinational company concerning the linear compressor, and is in talks with other U.S. and European companies. The Israeli company expects to have further prototypes available by the end of this year.

As for the automotive air conditioners, Medis El has its skeptics. Berchowitz of Global Cooling, for example, is among the many who do not believe that a Stirling cycle-based system can work in a car, because vehicle climatization requires a high output of heat over a small temperature range.

However, Medis El calls for a new concept, whereby each of four passengers would have 100 W of cooling capacity devoted to him by a segmentation of the system. The heat exchanger of Medis El's displacer/expander has a surface that is multiplied many times by 1,000 drilled holes and hundreds of grooves. This increase of the exchanger's surface area allows far better heat dissipation, said Zvi Rehavi, the executive vice president and general manager of Medis El.

Medis El also calls for its Stirling air conditioner to be electrically connected to the inverter and not mechanically to the car engine. The arrangement avoids the system slowdown one gets when the engine is idling and permits a smaller air conditioner to serve climatization needs, according to Rehavi.

If Medis El can give its air conditioner a commercial launch, there is a potential market in electric vehicles. The relatively low energy output of electrical motors may make Rankine cycle compressors impractical.

The company said it is courting a partnership with automotive air conditioning suppliers in Japan, Europe, and the United States.

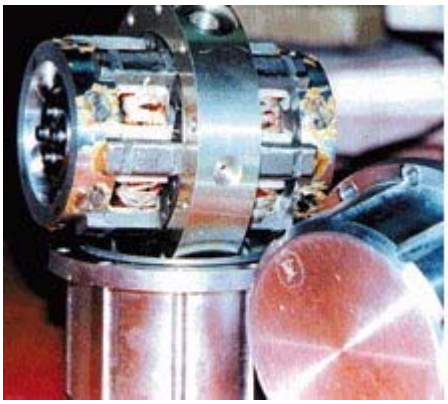
Independent engineer Steve Feher of Honolulu expects the next generation of car seat climatization systems to be run from Stirling coolers. Feher licensed Amerigon Corp.

of Los Angeles to develop and license a total of 39 carmakers to use his current-generation thermoelectric car seat climatization system. He strongly believes that the next generation will go Stirling, and says engineers from Lear Corp. in Southfield, Mich., are interested.

Containing the Helium

One of the trickiest aspects of the new-generation Stirling cycle systems for refrigeration is the proper containment of the helium.

Berchowitz of Global Cooling said that in the prototypes, about 0.2-liter of helium is hermetically sealed in the casing at a constant pressure of 23 bar, though that fluctuates by 10 to 15 percent. "Even though helium is a very small molecule, it is easily contained since it's not reactive," he said. "I can't divulge all the details, but we have tested a number of machines for leakage and they show that a 20 percent loss of charge would take in excess of 100 years."



Medis El of Tel Aviv, Israel, produced this prototype of a Stirling cooler to be the basis of a car climatization system it designed. Others are skeptical of any air conditioning application.

The scientists at Medis El and others point out that the very low-temperature cryogenic coolers based on Stirling compressors that have been used mainly for military applications (like cooling electronics for better performance) were not adaptable to consumer applications. The mean time between failure of these systems is 1,000 to 2,000 hours, and a refrigerator buyer expects at least 20 years. What's more, the military versions cost thousands of dollars.

McEntee, a Sunpower alumnus, points out that the military often did not have to confront the long-life barrier. In the common missile guidance application, for example, the Stirling cryocoolers for the infrared guidance electronics have to perform only as long as their hosts, the missiles. Until the missile is used, the military takes great care to run the cooler for a half-hour each

month. It is engineered to withstand this activity—which isn't quite the same as constant operation—for 15 years. Once the target is hit, the cooler obviously doesn't have much more life in it. Also, the military, at the time the coolers were developed at least, could afford to pay the "extremely expensive" prices the Stirling cryocooler would garner.

Alongside Medis El, Sunpower, and Global Cooling is a Christchurch, New Zealand, company called Whisper Tech Ltd. Whisper Tech is making prototypes of a PPS 16 alternating current home-scale generator, a co-generation engine that also provides heat.

The PPS 16 system is designed to be connected to the electricity grid and work with a home's central heating boiler. Whisper Tech chose not to use the free-piston configuration for its Stirling machine. It uses the more traditional crank, or kinematic, design, but employs a patented "wobble yoke" that, according to Whisper Tech, allows for a compact engine with little vibration.

According to Don Clucas, technical director at Whisper Tech, under the right conditions home energy conversion devices can be as efficient as condensing boilers, more than 90 percent. Transmission losses at the same time are negligible.

The New Zealand power authority Orion (formerly Southpower) is a major shareholder in Whisper Tech. According to Rangi de Abaffy, customer services manager at Whisper Tech, about 100 prototype PPS 16s will be available for sale next year. These will produce 750 W of 230 V ac on continuous duty, with co-generation providing 6 kW for heating water or spaces. The fuel used daily will be about equal to that consumed by a home boiler, according to Whisper Tech, but the type of fuel is flexible. Typical options will be natural gas, diesel, or kerosene. The system is electrically started, and it regulates its own heat and power. It can be programmed by the user.

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