Gas-Fired Residential Heat Pump Water Heaters: An Exploration and Evaluation of Potential Technologies

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Gas-fired water heaters currently account for more than 8% of the total residential energy use in the United States on a source basis. The energy factor (EF) of typical gas-fired storage water heaters now being sold is 0.55. This is the lowest average efficiency of any major gas consuming comfort appliance in U.S. homes. The most efficient gas-fired water heater available has an EF of 0.86. There are several possible gas-fired heat pump technologies that could be applied to domestic water heating. Any of these would bring dramatic increases in efficiency to gas-fired water heating. This paper reviews and evaluates several possible gas-fired heat pump technologies for domestic water heating. An absorption cycle using ammonia and water is the most promising. Another likely technology is chemisorption using ammonia and metal salts. Among the other gas-fired technologies considered here are; solid sorption cycle, vapor compression heat pumps driven by internal combustion or Stirling engines, duplex Stirling or Vuilleumier cycle, duplex thermoacoustic, and thermosyphon hydraulic compressor. An electric heat pump driven by electricity generated by the water heater from natural gas is considered a gas-fired heat pump water heater for purposes of this paper. Four technologies, thermoelectric, thermionic, thermophotovoltaic, and the fuel cell, for generating electricity to drive electric heat pumps are reviewed. Some electric heat pump technologies considered are vapor compression cycle, thermoelectric cooling, Stirling cycle, thermoacoustic, and hydraulic compressor. Brief descriptions are given for all technologies. Current development status, potential problems, and subjective estimates of EF and mature market manufacturing costs are also included.

Introduction

Gas-fired water heaters currently account for more than 8% of the total residential source energy use in the United States or about 1.161015 BTU/yr (0.34 PWh/yr) (Energy Information Administration 1993). At the household level, heating water is usually the second or third most intensive energy end use. The efficiency of gas-fired storage water heaters is poor compared to furnaces and boilers, although it is considerably better than electric resistance on a source energy basis. Water heaters are rated by EF. EF is a measure of average daily efficiency including standby losses based on a 24 hour simulated use test. The EF of typical gas-fired storage water heaters now being sold in the U.S. is about 0.55. This is a much lower average efficiency than furnaces or boilers. (Minimum efficiency standard for furnaces is an AFUE of 78. Condensing furnaces with an AFUE of over 90 account for a sizable fraction of current shipments. The minimum efficiency standard for boilers is 80.) Recovery efficiency, a measure of instantaneous efficiency, is usually about 75-78% (GAMA 1993).

There are approximately 50 million households currently heating water with gas-fired water heaters. Annual shipments are about 4 million per year (Appliance 1991). The typical gas-fired storage water heater currently being sold in the U.S. consists of a glass-lined steel tank above a circular burner. Combustion gases are passed through a center flue, which also acts as a heat exchanger. The exterior of the tank is insulated with 1 inch (2.5 cm) of polyurethane foam. Ignition is provided by a continuously burning pilot. Because of the open center flue and the standing pilot, standby losses account for about 26% of energy consumption (Paul et al. 1991). The most efficient currently available model[1] has an EF of 0.86 (GAMA 1993).

Research and development efforts to commercialize gas-fired space heating and cooling technologies are being undertaken by several groups. These gas-fired heat pump technologies could potentially be applied to domestic water heating. Most of these would double the recovery efficiency for gas-fired water heaters and result in a large reduction in energy consumption for this end use.

Design Concerns

Important design issues for gas-fired water heaters are first cost and installation. Perhaps more than any other household appliance, consumer choice of water heaters is driven by first cost. Lack of awareness of operating cost by consumers is one reason for this. Hot water use is nearly constant throughout the year (Thrasher et al. 1990), unlike air-conditioners or furnaces. Therefore consumers usually don't pay much attention to the cost of their hot water. Also the purchaser of the water heater is often not the person who will be paying the gas bills, for instance a landlord for rental units or a contractor for new construction. These purchasers have no interest in reducing operating cost, only in reducing first cost. Replacement purchases usually are the result of a complete failure of the existing water heater. In emergency replacement situations, rational economic decisions are often short circuited. When the water heater is leaking all over the floor and the shower is ice cold, about the last thing most people think about is operating cost. The priority is getting hot water back on as soon as possible.

These pressures to limit first cost have resulted in low prices for water heaters compared with other appliances. The typical installed consumer cost for a gas-fired water heater is about $300, with annual operating costs of about $160 (LBL 1993; Paul et al. 1991). A technology that doubles recovery efficiency, without changing heating rate or standby loss, would effectively cut operating cost in half. To realize a four year payback, with this type of efficiency increase, the initial cost to consumers could double. This is a very formidable design cost constraint.

Installation concerns are also important for water heater design. The continuously burning pilot allows water heaters to be installed without electricity. 51% of existing water heaters have no electricity within 8 feet (2.5 m) (Paul et al. 1991). Most of the heat pump technologies examined here would require some electricity for pumps and/or fans. This electricity could either be self-generated or acquired from standard house wiring. In either case there would be an extra cost for providing electricity.

The combustion products for gas-fired appliances need to be vented outside the living space. If the efficiency of the appliance is too high, the combustion products in the flue may become cool enough to condense in the venting system or within the appliance itself. This increases the potential for corrosion and can lead to potentially dangerous situations (Paul et al. 1991). If the steady-state efficiency is high enough, as with condensing technologies, the products of combustion can be cooled to a temperature low enough to vent through inexpensive plastic. Heat exchangers for these designs must be corrosion resistant, which adds to the expense of the unit (Patel et al. 1993). An alternate method of venting with low temperature plastic is to draw additional outside air into the venting system to dilute the flue gases to low enough temperatures [2].

If the unit is larger than standard or existing water heaters, installation will become more difficult and therefore more costly. Most water heaters are currently small enough to fit through doorways during installation or replacement (ADM 1987; Paul et al. 1991). This should be considered in new designs.

Increasing the storage capacity of water heaters allows the heat input rate to be reduced. This is a valuable consideration for heat pump water heaters, where the cost of the heating unit is likely to be significantly higher than the cost of increasing the size of the storage tank. Reduced size of the heat pump has reduced the cost of recently developed electric heat pump water heaters (EPRI 1993). Typical gas-fired storage water heaters have an input rating of 34 kBtu/hr (10 kW). The rate of heat input to the water is 26 kBtu/hr (7.6 kW). The average daily burner operating time, at this input level, is about 2 hours per day (LBL 1993). This suggests that a water heating rate as low as 2.5 kBtu/hr (0.73 kW) could theoretically be sufficient. Although this is too low for practical use, the electrical heat pump water heater noted earlier has a nominal heating rate of 6.5 kBtu/hr (1.9 kW) and performs adequately for most households.

Technology Possibilities

An extensive literature search was conducted to find references to technologies that could be used for gas-fired heat pump water heaters. Only two references were found that mentioned gas-fired heat pump water heaters (Herold et al. 1991 May; Patel et al. 1993). Several references were found for gas-fired cooling technologies. These technologies were usually being developed to provide both heating and cooling and also for much larger loads than are required for water heating. These could be used for water heating by cooling ambient air and applying the rejected heat to water.

Another method of using gas for heat pump water heating is to generate electricity to power an electric heat pump water heater. The waste heat from the electrical generation process can also be used to heat water, as in a co-generation system. This would result in effective electricity generation efficiencies approaching unity, much higher than typical utility system efficiencies. A few potential electricity generating technologies are also included here.

Table 1 lists all the technologies considered in this paper. Technologies are grouped into sections. The first section covers heat pump technologies that are strictly gas fired, or would only require a minimal amount of electricity to run small pumps, fans, controls, etc. The second section lists electric heat pump technologies that could be incorporated into a gas-fired heat pump cogeneration system. The third section lists technologies that could be used for very small scale generation of electricity from natural gas.

Within sections the technologies are listed in estimated order of availability. Early availability means that the technology is commercially available, at least in small numbers, or expected to be within a year, although usually for a different end use or scale. Medium availability indicates that a prototype has been built, again usually for a different end use or a different scale. Late availability indicates that no prototypes have been built. Also listed in the table are projected efficiencies and costs. Because of the speculative nature of this report and because the author is not aware of anyone conducting research and development efforts on residential gas-fired water heaters, only very subjective, qualitative estimates are given. The EF for heat pump technologies listed in the table is in comparison with other heat pump technologies, not to standard gas-fired water heaters. 'Low' implies an EF close to unity. For electric generating technologies, a low conversion efficiency means about 15% or less of the energy content of the gas is converted to electricity. 'Very high' conversion efficiency, indicates processes at or above the Carnot efficiency. Estimated costs were based on the relative mechanical complexity of the systems and the availability of materials used. Moderate cost was for an estimated mature market incremental cost in the $300 to $500 range. Costs for electric generating technologies (and thermoelectric cooling) are the most speculative. Discovery of advanced materials with more suitable properties could dramatically change some of these costs. Following is a short discussion of each technology.

Absorption

In a basic absorption cycle, low-temperature refrigerant vapor is converted to a liquid by going into solution with an absorbent. Thermal energy is released at this stage of the process in the absorber. The refrigerant-absorbent solution is then pumped to a higher pressure at the generator, where the refrigerant and absorbent are separated by what is essentially a distillation process. This requires high temperature heat input. The high temperature refrigerant vapor is condensed to a liquid by the release of thermal energy. The hot liquid refrigerant is expanded into the evaporator where it is evaporated at low temperature and pressure. The heat drawn into this low temperature evaporator provides the cooling effect of the cycle (ASHRAE 1989). Improvements in efficiency can be gained by splitting the generator and condenser into two or more stages. The heat from the first stage condenser is added to the second stage generator to boil out more refrigerant. Clever use of heat exchangers and mass transfer can also increase the efficiency. Common refrigerant/absorber pairs are ammonia/water and water/lithium bromide.

Current uses of absorption cooling are for central chillers and refrigerators for recreational vehicles (Nadel et al. 1993; Wilkinson 1994). One manufacturer in the U.S. has been producing gas-fired air-conditioners using absorption technology for several years, although it is only a single effect absorption cycle and not very efficient. Interest in absorption cooling is reviving because many electric utilities are facing summer peak loads that are approaching capacity. Gas utilities are interested in increased summer load to level their annual capacity factor. Also, most absorption cycles do not use ozone depleting chemicals.

A unit using a generator-absorber heat exchange (GAX) cycle based on ammonia and water is nearing commercialization for residential space heating and cooling (Nadel et al. 1993; Phillips 1990). By taking advantage of the water heater storage tank to reduce heat pump size as outlined earlier, the 72 kBtu/hr (21 kW) output of this unit could be scaled down 10 times and still provide adequate hot water. A smaller water/lithium bromide double effect absorption cycle is also under development by a gas utility (Fujino 1992). Although cost will not scale directly with heat output, sizable reductions in cost could be expected. Furthermore, water heaters are never called upon to cool water, so some additional cost reduction can be expected by making the unit work in heating only mode. Integrated heating, cooling, and water heating GAX cycle appliances are more likely, given current market forces, and only after heating and cooling GAX cycle appliances have become commercialized and profitable.

Internal Combustion Engine

This is essentially a vapor compression heat pump driven by an internal combustion engine. Engine cooling water is used for additional heat in the heating mode. There is no question that this technology can be used to make gas-fired heat pumps. These have been available in Japan since the early 1980s (Nadel et al. 1993). A major air-conditioner manufacturer has been field testing an internal combustion engine driven residential heat pump in the U.S. (Klausing et al. 1993). Production is expected to begin this year. The engine used in this unit is a single cylinder, four-stroke 5 HP (3.7 kW) reciprocating engine. Because of the complexities of the internal combustion engine, this technology would not be easy to scale down to a size appropriate for residential water heaters.

Table 1. Review of Residential Gas-Fired Heat Pump Water Heater Technologies

Technology	Availability	EF[(a)]	Cost
Absorption	early	moderate - high	moderate
Engine Driven Vapor Compression	early - medium	moderate	high
Solid Sorption	medium	moderate	moderate
Chemisorption	medium	moderate - high	low - moderate
Stirling Engine Driven Vapor Compression	medium	moderate	high
Duplex Sterling/Vuilleumier	medium - late	moderate - high	moderate - high
Duplex Thermoacoustic	medium - late	moderate	moderate
Thermosyphon Hydraulic Compressor	late	low - moderate	high - very high
Whistling Burner Thermoacoustic	late	low - moderate	low - moderate
Electric Heat Pump Technologies			
Vapor Compression Cycle	current	high	moderate - high
Thermoelectric Cooling	early - medium	low	high
Stirling Cycle	medium	moderate - high	moderate
Thermoacoustic	medium	moderate	low - moderate
Hydraulic Compressor	medium - late	moderate	high
Electric Generation Technologies		(conversion efficiency)	
Thermoelectric Power	early - medium	low - moderate	high
Thermionic Power	medium	low - moderate	high
Thermophotovoltaic Power	medium	low - moderate	high
Fuel Cell	medium - late	high - very high	high - very high

(a) EF is compared among heat pump water heater EFs, not to the EF of gas-fired water heaters.

Consequently, the estimated cost in Table 1 for this technology is listed as high. Maintenance costs could also be an issue.

Solid Sorption

This system takes advantage of the ability of activated carbon to adsorb ammonia. Two sorbent beds of activated carbon alternately pull low pressure ammonia from an evaporator and discharge it to a high pressure condenser. The condenser and evaporator, with a throttling device between them, provide the same function as in a vapor compression cycle. Each bed is alternately heated and cooled by a heat exchange fluid. As a sorbent bed is heated, the ammonia is desorbed, raising the pressure in that bed. The other bed is cooled and ammonia is adsorbed, dropping the pressure in that bed. By proper design of heat exchangers and fluid piping in the sorbent beds, most of the heat drawn from the sorbent bed being cooled can be used to heat the other bed (Sanborn et al. 1992).

A prototype of this technology for space heating and cooling has been built, and commercialization is actively being pursued. This technology may be easier to scale down to residential water heater sizes than vapor compression technology. There are few moving parts and the components are not as complicated as with vapor compressors. However the carbon beds are quite large and heavy.

Chemisorption

Chemisorption is similar to solid sorption in form but takes advantage of the weak chemical bonds that ammonia forms with metal inorganic salts. These ammoniated salts can bond 3 to 5 times as much ammonia as activated carbon, This higher adsorption capability means smaller equipment requirements and lower first costs. The adsorption rates are also faster than in other solid sorption systems. The large variety of salts available allows a wide choice of temperatures and pressures to be used. Different salts can be used in separate beds in two more stages to gain additional efficiency. Another way to gain efficiency is to pack multiple layers of different salts in each bed arranged in order of temperature at which adsorption and resorption occurs. The hot heat exchange fluid is cooled to successively lower temperatures by the resorption of each salt layer it passes through in the high pressure bed. On the other side of the fluid loop, it picks up the heat of adsorption at progressively higher temperatures as it passes through the salt layers in reverse order in the low pressure bed. Using proper salts, the efficiencies of this process can be quite high.

Breadboard and prototype residential sized heat pumps have been made with this technology. Ammonia holding and pumpout systems based on this technology are currently available (Rockefeller et al. 1992; Ryan and Rockefeller 1992).

Stirling Cycle

In a Stirling cycle, a fixed amount of gas alternately expands and contracts between 2 pistons driven by the constant temperature difference between a hot source and a cold source. Heat is stored in a regenerator as the gas passes through it in one part of the cycle and reused as the gas passes back through the regenerator later in the cycle. The heat for the hot source can be supplied by an external combustion source. External combustion burners can be made to bum with low emissions much more easily than in internal combustion engines. The ideal Stirling cycle efficiency matches the Carnot efficiency (Burghardt 1982). Helium gas is often used as a working fluid, but air and nitrogen have also been used. The Stirling cycle can be used as a heat engine or a heat pump and can be built with fewer moving parts than an equivalent internal combustion engine. When used as a heat engine, it can drive a standard vapor compression heat pump or a Stirling heat pump in a duplex Stirling machine. A Vuilleumier system is similar, except that the engine and heat pump are unified in a single cycle, with three temperature zones instead of two (Finkelstein 1992). Stirling cycle heat pumps are often used in cryogenic refrigerators (Williamson et al. 1987). Development has been limited by difficulties in designing regenerators and piston seals. Although there have been many research and development efforts on residential sized Stirling cycle engines and heat pumps, most seem limited so far to experimental prototypes (Gonnov and Loktinov 1993; Kagawa et al. 1992; Shinozaki et al. 1992; Shonder et al. 1992). Federal funding for further development work has apparently ceased in the U.S. (Patel et al. 1993). Research and development efforts for Stirling engine driven heat pumps still continue in other parts of the world.

Thermoacoustic

Thermoacoustic refrigeration uses high intensity sound waves to pump heat with inert gases as the working fluid. As the working fluid oscillates back and forth, it changes in temperature because of the compression and expansion caused by the pressure variations associated with a standing sound wave. Changes in temperature are also associated with changes in location along thin plates arranged in a stationary stack. The portions of the gas that are compressed transfer heat to the plates, the expanded portions draw heat from the plates. The irreversibility caused by the imperfect thermal contact between the acoustically oscillating gases and the plates causes the proper phasing of the cyclic refrigeration processes of compression, expansion, regeneration, etc. This leads to a temperature differential along the thin plates. A heat exchanger is attached to each end of the stack of plates. One becomes cold as the other is heated (Garrett and Hofler 1992).

There might be a couple possible methods to use this technology for gas-fired heat pump water heating. One is to assemble two acoustic refrigeration units back-to-back. The first one is heated and used as a heat engine to generate intense sound. The second refrigeration unit is driven by the sound from the first one. Or, the intense sound needed to drive the thermoacoustic cycle could be created by a loudspeaker powered by electricity generated from any of the technologies listed above. Another option would be to design the gas burner as a sound source, like a steam whistle. Since most burners are designed to be silent, the feasibility of this option is not known.

The thermoacoustic refrigeration devices built so far have been for use in the U.S. space program. However, a major appliance manufacturer is involved in the development of the latest model that is similar in design and capacity to a home refrigerator. Consumer refrigerators based on this principle might be available to consumers within a few years (Lipkin 1994).

Hydraulic Compressor

Hydraulic compressors work by bubbling warm refrigerant vapor into the top of a long column of carrier fluid. As the carrier descends, the gas is compressed and liquefied by hydrostatic pressure. The heat from compression is transferred to the carrier fluid. At the bottom of the column is a gravity separation chamber where the refrigerant liquid is separated from the carrier fluid. The carrier fluid is then pumped back to the top of the column, while the refrigerant is passed through an evaporator. Column height is 100 feet, although double or triple staging could reduce that to 50 or 35 feet (Nadel et al. 1993). Presumably the carrier fluid could be driven by a heat source in a thermosyphon loop.

The main drawback for this system is the height of the column. This would create a very high initial cost. A space cooling unit using butane and water is under development.

Thermoelectric Effect

An electric current applied across two junctions of dissimilar materials will heat one junction and cool the other. Conversely by heating one junction and cooling the other, electricity will be created. So far, the efficiencies have very been low. Recent discoveries might have revealed ways to dramatically increase efficiencies (Aspden and Strachan 1993). The technology has no moving parts, is very reliable and can be scaled to very small dimensions. Currently both thermoelectric refrigeration and thermoelectric power generation are available, mostly for specialty uses such as cooling electronics, small refrigerators, and power remote radio broadcasting stations. Current models use semiconductors such as lead-tellurium or silicon-germanium. For power generation, the hot surface temperatures are around 600°C, while the cold side temperatures are between 100 and 200°C. Research and development is proceeding on the application of thermoelectric power generation to both residential furnaces and water heaters, Both technologies are ready for field testing now. The motivation is to provide electricity for appliance components such as blowers and ignition systems without relying upon utility supplied electricity. Thus consumers could avoid losing heat or hot water when the electric utility grid is disabled, as occasionally happens during severe storms (Nadel et al. 1993; Valenti 1993). It may also make installation easier, because the appliance would not have to be supplied with electricity. To provide enough electricity to drive an electric heat pump will require significant scaling up beyond these auxiliary power uses.

Thermoelectric power generation could supply electricity for pumps, controls, and ignition systems for other gas-fired heat pump technologies. It could even be used to power electric heat pumps or power a thermoelectric cooling system and use the hot junction as a heat source. In any of these applications, the waste heat from the inefficiencies in electricity generation would presumably be used to heat the water. Thus, in effect, the electricity generation can be nearly 100% efficient. Using this with an electric vapor compression heat pump would be expensive. Given the inefficiencies of the thermoelectric power generation process, only a small portion of the input would be available as electricity. The electric vapor compression heat pump would be supplying only part of the heat to the water. This would result in an inefficient, expensive system. The ability to make small thermoelectric cooling units would mean that the overall price of using one as a heat pump would be less than an electric vapor compression heat pump, but that the efficiency would also be lower.

Thermionic Power

Thermionic converters generate electricity by heating an emitter or cathode to provide sufficient energy to lift electrons beyond the retaining force on the surface. The electrons are collected on a cooler anode after crossing a short vacuum or gas-filled separating gap. The resulting voltage differences are tapped to provide power. Typical temperatures for the hot surface of a thermionic converter are 1600-2200 K. Electric conversion efficiencies are low, less than 10%. Some researchers are adapting thermionic converters developed for the Soviet space program for use on domestic hydronic boilers. This would take advantage of the high flame temperature of natural gas burners for electricity generation, while still leaving plenty of heat available for the hydronic heating system. These systems are being designed as household scale distributed cogeneration facilities. Electricity generated would be directed back toward the electric utility grid (Ruzhnikov et al. 1993; Veltkamp and van Kemenade 1993).

Electricity generated by a thermionic converter could be put to the same uses as that generated by thermoelectrically generated power. The process cannot be reversed to work as a heat engine, unlike the thermoelectric process.

Thermophotovoltaic Power Generation

Thermophotovoltaic (TPV) systems generate power by heating a ceramic emitter that has been designed to give off a specific frequency of light. The light from the emitter shines on a photovoltaic cell chosen for maximum conversion efficiency at the same wavelength. Photovoltaic cells have the potential of reaching light to electricity efficiencies as high as 50% in this application. Research is currently underway to develop TPV systems appropriate for residential furnaces and water heaters. Again the electricity is intended to power components such as fans and ignition systems of conventional furnaces and water heaters (Brown 1990; Valenti 1993). Advantages are reduced risk of losing heat during power outages and ease of installation, because the appliance does not have to be connected with line voltage.

The same considerations and options are available regarding heat pump water heating with this technology as with thermoelectric power generation. The electricity generation efficiencies are potentially higher, but development and commercialization of the TPV technology are not as far along as the thermoelectric or thermionic technologies are.

It may also be possible to combine all or some of the thermoelectric, thermionic, and thermophotovoltaic technologies into one unit, as they are each based on a different mechanism or temperature. TPV relies on radiation not temperature, and thermionic converters require higher temperatures than thermoelectric generators. Photovoltaic cells could be applied to the hot surface of a thermionic converter. The hot side of a thermoelectric generator could be applied to the cold side of the thermionic converter. This speculation by the author has not yet been investigated.

Fuel Cell

Fuel cells are devices that convert hydrogen-rich fuel sources directly into electricity. Because the conversion to electricity occurs at a chemical level, fuel cells are not limited to the Carnot cycle efficiency. Current fuel cells are achieving fuel to electricity efficiencies as high as 40%, with advanced designs having the potential of 60% conversion efficiency. Fuel cells have low emission levels, few moving parts, quiet operation and can be constructed in a wide range of sizes. Fuel cell technology is being actively pursued by electric utilities, the automotive industry and other research institutes (Fiskum 1993).

There are four major types of fuel cells that are currently being developed. The fuel cell technology closest to commercialization is the phosphoric acid fuel cell (PAFC). Many small utility power plants have already been built in the U. S., Japan, and Europe that use this technology. The earliest ones were installed in 1991. These plants are showing very low emission levels. PAFCs operate at temperatures around 200°C.

Molten carbonate fuel cells (MCFC) are also attracting significant interest from utilities. These fuel cells operate at higher temperatures, typically 650 - 700 “C and have the potential for higher efficiencies than other fuel cells. They are also capable of operating on coal gas. Several demonstration power plants are currently being planned or built. A 2 MW plant in Santa Clara, California is scheduled to begin operation this year.

Small utility scale solid oxide fuel cells (SOFC) are being field tested in several locations. These cells operate at 1000°C. Commercialization is projected for the late 1990s. Research and development activity for these fuel cells is being carried out in the U. S., Japan, Germany, and Australia.

These three fuel cell technologies are primarily being designed for utility scale operations. A fourth type, polymer electrolyte fuel cell (PEFC), sometimes called proton exchange membrane, is being developed for the transportation industry. A hydrogen fuel powered city transit bus using this type of fuel cell has been demonstrated in Vancouver, BC. These cells operate at the 80 “C - 90°C temperature range (Hirchenhofer 1993).

Current research on fuel cells has been focused on applications much larger than needed for single-family water heaters. Although they can be scaled across a large range of sizes, very small units would need additional research and development and may not be as efficient as larger units. Currently fuel cell technologies are very expensive.

Conclusions

There are many gas-fired heat pump and electricity generation technologies at various research and development stages. So far, none have been targeted for development as single-family residential water heaters. However, several of the technologies could be scaled down to that size. The ones that are farthest along the development path and most compatible with residential water heating are the absorption and chemisorption technologies. And even these technologies are still in development for space heating and cooling applications. Theoretically the highest efficiency system possible is a fuel cell powered electric vapor compression heat pump system, although the cost would be prohibitive for this use.

This paper is very speculative. Current development efforts for some of these technologies are targeting space heating and cooling applications. Integrating water heating onto these applications is probably going to happen sooner than development of gas-fired heat pumps for water heating only. However there are clearly gas-fired heat pump technologies becoming available that could be used for water heating.

Endnotes

1. SABH (U. S.) Water Heater Group, Polaris model.
2. See for example, A. O. Smith Water Product Co., Sealed Shot models of water heaters.

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