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ALTERNATIVE COOLING TECHNOLOGY OPTIONS

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ABSTRACT

This paper considers the alternative cooling technologies studied by Fisher et al. (1994) and assesses their current potential to compete with or to replace vapor compression refrigeration technology for space cooling and near-room temperature refrigeration applications. First, a taxonomy of cooling technologies based on the main energy input is presented. Then, several alternative cooling technologies are discussed with magnetic cooling and thermoacoustic cooling being discussed in most detail. For magnetic cooling and thermoacoustic cooling, a brief summary of the findings of Fisher *et al.* (1994) is presented followed by a discussion of the advancements since their study and the current state-of-the-art of the technologies. The paper includes a current assessment of the potential of each of the technologies to compete with or replace vapour compression technology for space cooling and near-room temperature refrigeration.

1. INTRODUCTION

The air conditioning and refrigeration industry (hereafter, "industry") is under increasing pressures to improve the energy efficiencies of its systems and to reduce their overall environmental impacts. The amount of energy consumed for space cooling and refrigerantion is enormous. As an example, space cooling and refrigeration in commercial and residential buildings account for 24.8 % of the total electrical energy consumption in the United States (DOE, 2009). Given increasing primary energy costs, the unequal distribution of primary energy reserves in the world, and political instabilities throughout the world, it is increasingly incumbent upon the industry to continuously improve the energy efficiencies of its systems.

A second issue linked to, but distinct from, the first is the industry's overall environmental impact. In particular, there are growing concerns regarding the direct and indirect global warming impacts related to refrigerants and their applications, the industry's overall impact on global climate change, and the overall societal costs associated with attempting to mitigate these negative impacts. Therefore, a question worth readdressing periodically is one regarding the prospect of alternative cooling technologies being developed to the point that they could compete with or replace, at least in part, the vapor compression technology that dominates space cooling and near-room temperature refrigeration applications.

One of the most thorough studies along these lines is a 1994 report by Fisher *et al.* (1994), which investigated ten alternatives that were emerging and/or were being developed at the time of the report and which held promise for potentially being able to replace vapor compression technology, and thus ultimately being able to eliminate the need for CFC and HCFC refrigerants. This paper revisits the status of a few of the alternative cooling technologies studied by Fisher *et al.* (1994) and assesses their current potentials to compete with vapor compression technology for space cooling and near-room temperature refrigeration applications. Due to space limitations in this paper, the discussion herein will necessarily be incomplete. Therefore, a more detailed and complete manuscript will be forthcoming to this publication.

2. FUNDAMENTALS AND APPLICATION CONSIDERATIONS

2.1. Ideal (Carnot) Cycle

Since the focus of this paper is on space cooling and near-room temperature refrigeration, it is convenient to refer to the Clausius statement of the Second Law of Thermodynamics, namely, "No process is possible in which the sole net effect is the transfer of energy from a system in a stable equilibrium state with a lower temperature to a system in a stable equilibrium state with a higher temperature (Gyftopoulos and Beretta, 1991)." A simpler, and perhaps less technical and precise, but equivalent, statement is, "A cup of coffee will never spontaneously get hotter while a room spontaneously gets colder." Hence, the purpose of space cooling and refrigeration systems is to transfer thermal energy from a low-temperature source to a high-temperature sink while utilizing the least amount of work, i.e. to maximize the Coefficient of Performance (COP) for a given capacity and source and sink temperatures.

In addition to COP, which is a performance index based on the First Law of Thermodynamics, it is convenient to compare different systems, or even the same system operating under different conditions, using a performance index based on both the First and Second Laws of Thermodynamics such as the one provided in eq. (1), which compares the COP to the ideal COP (i.e., $\mathrm{COP_{Carnot}}$).

$$\Phi = \frac{\mathrm{COP}}{\mathrm{COP_{Carnot}}} \tag{1}$$

2.2. State-of-the-art Performance

When evaluating the performance potential of alternative cycles, one needs to consider what the comparison benchmark is in order to be certain that an equal comparison is being made between different technologies and systems. For example, is the COP of the alternative technology based on an analysis of only the cycle (internal irreversibilities only) or does it also include external heat transfer irreversibilities which will almost certainly be included in an experimentally determined COP of a baseline vapor compression refrigeration cycle?

Since external heat transfer irreversibilities are not always included in efficiency calculations for alternative technologies, it is worthwhile to demonstrate the effects that external heat transfer irreversibilities have on the Second Law efficiency. Eq. (1) can be rewritten for a system where T_{evap} and T_{cond} are constant as:

$$\Phi = \frac{T_{\mathrm{H}} / T_{\mathrm{L}} - 1}{T_{\mathrm{cond}} / T_{\mathrm{evap}} - 1} \tag{2}$$

where all temperatures are in kelvin.

Figure 1 plots eq. (2) for T_{L} = 0 ^{0}C and T_{H} = 40 ^{0}C as a function of increasing driving temperature differences in the evaporator and condenser. Figure 1 shows, for example, that driving temperature differences of 10 ºC in both the evaporator and condenser reduce the Second Law efficiency by 35.8 %. Note: ΔT refers to the driving temperature difference between the sink or source and the condenser or evaporator, respectively.

When making comparisons among different technologies, one must take into account the continuing improvements made in baseline vapor compression equipment over time. For example, according to AHRI statistical profiles (Skaer, 2007), at the time of the Fisher *et al.* (1994) report, the average seasonal cooling efficiency, referred to as SEER, of unitary equipment shipped in the U.S. was 10.61 (equivalent to a COP of 2.80); whereas, in 2007 the average SEER value had climbed to 13.66 (equivalent to a COP of 3.60), a 28.7 % increase in average efficiency over a more or less fifteen year period. Today it is possible to purchase ultra-high efficient units with SEER values on the order of 22 (equivalent to a COP of 5.80). As noted by Calm and Domanski (2004), the "A" condition of standard ratings for unitary air-conditioning equipment corresponds to ideal cycle conditions of T_{evap} = 10 ºC and T_{cond} = 35 ºC, which yields a $\mathrm{COP_{Carnot}}$ = 11.3 (equivalent to a SEER value of 42.9). Therefore, the Second Law efficiencies of average unitary equipment shipped in 1994 was 0.248, in 2007 was 0.318, and today, ultra-high efficiency equipment can have values over 0.50.

3. ANALYSIS

3.1. Classification of Cooling Technologies

Figure 2 presents a taxonomy of cooling technologies based on the primary energy input (i.e., electrical, mechanical, etc.). This is, of course, not the only taxonomy that could be developed. For example, one could be developed based on operating temperature range (e.g., cryogenic, low-temperature, medium-temperature, high-temperature), one could be developed based on the phase of the working fluid (e.g., solid, liquid, gas, multiphase), one could be based on whether the primary energy input is in the form of mechanical work or thermal energy (heat), etc. Regardless, the divisions shown in Figure 2 are not exhaustive, and, in some cases, could be combined. The usefulness of the taxonomy shown in Figure 2 is that it categorizes systems first by the primary energy input and then subdivides them by the basic working principle and the "refrigerant".

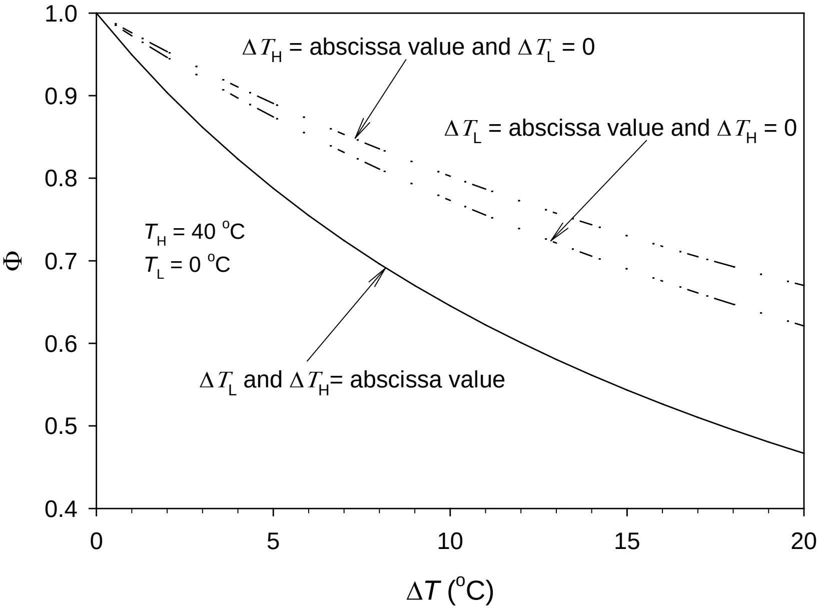

Figure 1. Impact of external heat transfer irreversibilities on the Second Law efficiency.

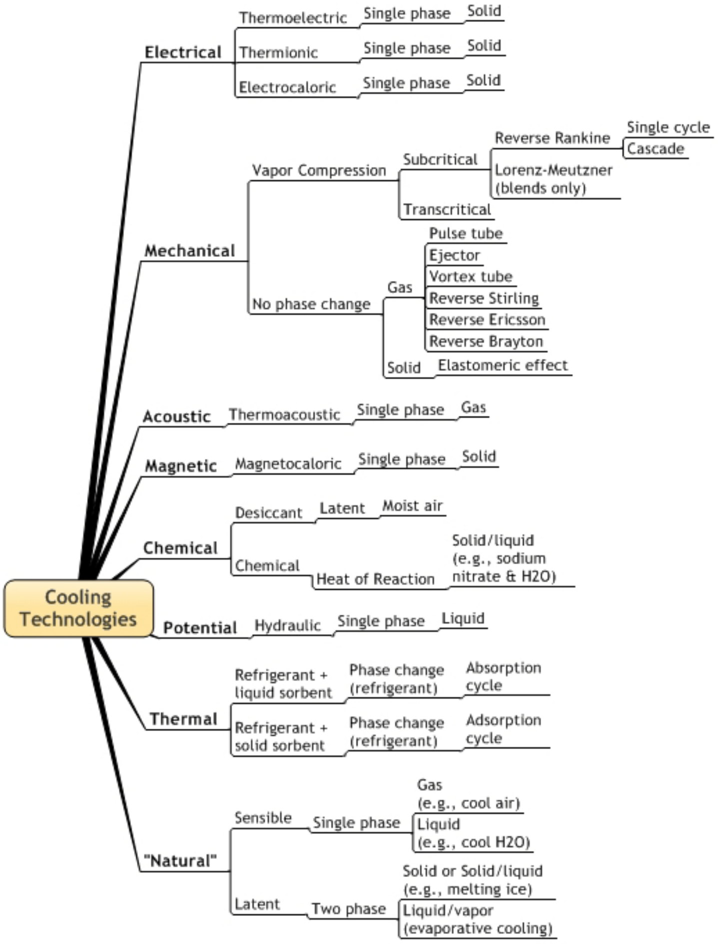

Figure 2. Taxonomy of cooling technologies.

3.2. Discussion of Alternative Cooling Technologies

Following is a discussion of different cooling technologies, which only can be discussed briefly because of the space limitation of the paper. Magnetic cooling and thermoacoustic cooling are discussed in more detail because of their novelty and due to considerable research interest in these technologies. Throughout, only a few select papers are referenced; an exhaustive bibliography is not claimed.

3.2.1. Low-Promise Options

While the report of Fisher *et al.* (1994) discussed hydraulic refrigeration, evaporative cooling, Stirling cycle refrigeration, Malone cycle refrigeration, and thermoelastic heat pump, their assessments at that time were that these technologies likely would not be able to compete with vapor compression technology for the foreseeable future for comfort cooling and near-room temperature refrigeration. A literature search by us revealed that little progress has occurred in any of these areas over the last 15+ years to fundamentally alter their assessments. Therefore, we affirm the assessments of Fisher *et al.* (1994) regarding these technologies and thus will not discuss them any further in this paper.

In addition to the technologies discussed by Fisher *et al.* (1994) a few others are worth mentioning. Our general assessment of these technologies is that they are, and for the foreseeable future will be, unable to compete with vapor compression technology. They are: (a) Ranque–Hilsh tube or vortex tube (see, e.g., Simões-Moreira, 2010 who achieved a $\Phi \approx 0.05$ when testing an air-standard cycle Ranque-Hilsh tube), (b) various gas cycles (e.g., Ericsson cycle [see, e.g., Hugenroth *et al.*, 2008 who achieved a $\Phi \approx 0.03$ when testing a liquid-flooded Ericsson cycle cooler] or Brayton cycle), (c) pulse tube refrigerator (used in cryogenics but is not competitive for comfort cooling), (d) Einstein absorption cycle (see, e.g., Mejbri *et al.*, 2006 who discuss the feasibility of the Einstein refrigeration cycle and conclude that air-cooled chillers based on the cycle are not feasible), and (e) ejector cycle refrigeration (see, e.g., Pridasawas and Lundqvist, 2007 or Angelino and Invernizzi, 2008 who both point to the low cycle efficiency of ejector cycle refrigeration; however, the cycle continues to be investigated for heat driven systems, e.g., Dennis, 2010).

In addition, we will not discuss thermionic or thermotunneling cooling any further in this paper after the brief remarks provided below despite the fact that the recent report by Brown *et al.* (2010) include them among their five most promising alternative cooling technologies. Perhaps among the two, the easiest for us to dismiss immediately is thermionic cooling since Brown *et al.* (2010) assess it as having the lowest potential of any of the five alternative cooling technologies they discussed in detail in their report. On the other hand, they rank thermotunneling cooling as third, ahead of both thermoelectric and thermionic citing its theoretical performance as similar to that of vapor compression technology and pointing out the large number of patents held by a private company, which may serve as an indicator of a rapid R&D effort. We disagree with this assessment. In our opinion, the simple facts that a commercial enterprise invests in research and development and seeks intellectual property protection are insufficient to justify the conclusion that the technology holds promise to compete with vapor compression technology. In fact, even if all technical barriers associated with thermionic and thermotunneling cooling can be overcome, these technologies are more likely to be applied for small cooling capacity and high heat flux applications, e.g. electronics cooling, because of expected difficulties in scaling them to capacities required in comfort cooling and near-room temperature refrigeration applications. Moreover, a review by us confirms that little research and development activity is occurring for these two technologies other than for spot cooling of electronics.

3.2.2. Magnetic Cooling

Physical Principle: Magnetic cooling is based on the magnetocaloric effect (MCE): most magnetic materials warm adiabatically when subjected to a magnetic field. For normal magnetocaloric materials, magnetization will lead to heating of the material, and demagnetization will lead to cooling of the material. An important parameter for characterizing magnetic cooling is the Curie Temperature, which is the point where a ferromagnetic material loses its permanent magnetism and becomes paramagnetic. The magnetocaloric effect is most pronounced near the Curie Temperature. Increasing the magnetic field intensifies the effect.

According to Kitanovski and Egolf (2010), most heat pump prototypes either are based on moving magnetocaloric materials through a static magnetic field or by moving a magnet mechanism relative to a static magnetocaloric material bed. In either case, as the magnetocaloric material heats or cools, it can be coupled to an external heat transfer fluid to realize a heat pumping effect. For comfort cooling and refrigeration, the most suitable materials are ones which have a Curie Point near-room temperature: one such material is the rare earth metal gadolinium.

Assessment of Fisher et al. (1994): Design studies had been performed for rotary magnetic-based machines and their efficiencies and performances predicted for various operating conditions; however, only one working prototype at Los Alamos Laboratory was noted. One of the largest hurdles noted to developing magnetic heat pumps was the lack of availability of low-cost, room temperature superconducting materials. They noted one study from the early 1990s by the Electric Power Research Institute that indicated it would take 15+ years for the materials to become available.

Advancements and State of Technology: Since the report of Fisher *et al.* (1994), there has been considerable research activity indicated by the sheer magnitude of papers and patents that have been published during the 2000's. For example, Gschneidner and Pecharsky (2008) report that prior to the discovery of the giant MCE (explained below) in 1997, approximately 10-20 papers were published annually with the word "magnetocaloric" in the title, abstract, or among the keywords, and that after 1997 the number of papers increased rapidly reaching well over 250 per year by the time of the writing of their paper in 2007. A second example is that the first International IIR Conference on Magnetic Refrigeration at Room Temperature was held in 2007, with the fourth having being held in August 2010, where over 45 papers were submitted. A third example provided by Yu *et al.* (2010) is the number of European patents issued for magnetic refrigerators and heat pumps. In particular, during the period 1997-2009, a total of 135 patents were issued, with 68 % of them issued during 2002-2009.

Several major breakthroughs have been made over the last decade or so, a few of which will be highlighted here. First, as noted by Gschneidner and Pecharsky (2008), a team led by Pecharsky and Gschneidner discovered in 1997 the so-called giant MCE in $Gd_5(Si_2Ge_2)$, which has a MCE that is approximately 50 % greater than that of pure gadolinium and a Curie Temperature of 270 K versus 294 for pure gadolinium. Second, as noted by Yu *et al.* (2010), Astronautics Corporation of America successfully developed in 2001 the world's first room temperature magnetic refrigerator based on permanent magnets. Third, as noted by Engelbrecht *et al.* (2007), layered regenerator beds consisting of layers of several MCE materials were developed with the promise to increase system performance. Fourth, as noted by Yu *et al.* (2010), there are now 41 working prototypes that have been built and are (or were) operating since the first room temperature machine was introduced by Brown (1976).

The research activity noted above, as well as other activity, continues. For example, extensive materials research is ongoing, where state-of-the-art materials (Gschneidner *et al.*, 2010) are the $La(Fe,Si)_{13}H_y$ family, NiMnGa shape-memory alloys, $MnFeP_xGe_{1-x}$ alloys, and $Gd_5(SiGe)_4$ intermetallic compounds.

In addition to material research, prototypes continued to be designed, developed, and tested, although all of the prototypes designed and developed to date have been small capacity machines. For example, of the 41 working prototypes (Yu *et al.*, 2010), the maximum cooling capacity is 600 W, and of the 19 machines with reported cooling capacity, the average cooling capacity is approximately 125 W.

Despite the presence of these 41 working prototypes and the ongoing work, the literature lacks reliable experimental data for comparing magnetic refrigeration and vapor compression technology: only three of the machines report some efficiency measurements. In particular, a permanent magnet refrigerator produced a maximum cooling power of 540 W with a COP of 1.8 at a temperature lift of 0.2 ºC (Okamura *et al.*, 2007), and a permanent magnet refrigerator produced a COP of 1.6 with a cooling capacity of 50 W and a temperature lift of 2 ºC (Tura and Rowe, 2009). Both of these machines are inefficient with very low values of Φ. Gschneidner and Pecharsky (2008) report that a superconducting magnet refrigerator (Zimm *et al.*, 1998) produced a cooling capacity of 600 W with a COP of nearly 10 ($\Phi \approx 0.6$) with a temperature lift of 10 ºC; however, at a temperature lift of 22 ºC, the cooling capacity dropped to 150 W and a COP of 2 ($\Phi \approx 0.2$).

Overall Assessment: Considerable research and development activity needs to continue in MCE materials, magnets, regenerators, system modeling, and systems engineering. Considerable steps need to be made to scale-up the cooling capacities and temperature lifts so that they are both appropriate for comfort cooling. Considerable activity needs to be undertaken to address some of the irrversibilities, such as, hysteresis, coupling to an external heat transfer fluid, internal conduction, and large pressure drops through the regenerator bed (single-phase flow), if present. Considerable activity needs to be undertaken to provide system performance test results so that reliable comparisons can be made with other technologies. Finally, R&D efforts must address materials and system costs, the processing of large quantities of MCE materials, and the larger size required per cooling capacity as compared to conventional vapor compression technology (Engelbrecht *et al.*, 2007). Hirano *et al.* (2010) highlight a large Japanese research effort in which they hope to move from the COP value of 1.8 of Okamura *et al.* (2007) to a COP above 10; however, no timeline or research details are provided.

Therefore, for the next twenty year period, our assessment is that it is likely that intense research and development activity will continue in the area of room temperature magnetic cooling, and that, if there are significant technical breakthroughs it has the potential to be implemented in small applications (e.g., household refrigerators).

3.2.3. Thermoacoustic Cooling

Physical Principle: Thermoacoustic cooling is based on the conversion of acoustic energy to thermal energy: The presence of an acoustic wave (standing or travelling) expands and contracts a working fluid (gas). As the gas expands, its pressure and temperature are reduced; likewise, as the gas contracts, its pressure and temperature are increased. In addition, the pressure differences lead to movement of the working gas. Finally, to achieve cooling and heating, the working gas must be coupled to an external heat transfer fluid through heat exchangers.

Thermoacoustic devices are contained in a sealed pressure vessel and consist of an acoustic driver (e.g., loudspeaker) which radiates acoustic energy into a resonator containing a porous “regenerator” or “stack”. The “regenerator” or “stack” serves to allow the working fluid (gas) to displace within it and serves to transfer thermal energy to and from the gas. The “cold” and “hot” heat exchangers are used to transfer thermal energy to and from an external working fluid. The acoustic waves can be either standing-wave or traveling-wave, which Garrett (2004) uses to classify thermoacoustic refrigerators as either: (1) standing-wave stack-based devices or (2) traveling-wave (acoustic-Stirling or pulse-tube) regenerator-based devices. The distinction he makes between “regenerator” or “stack” is beyond the scope of the present discussion; however, the terms are used to distinguish the physical geometry, where a non-dimensional number (Lautrec number) which compares hydraulic radius to thermal penetration depth is used to make the distinction. In any case, a “regenerator” or a “stack” serves the same purposes; therefore, hereafter, we simply refer to them as: regenerator. The technical differences between standing-wave and travelling-wave devices will not be discussed further here, other than to note that the acoustic network of a travelling-wave device is more complex than that of a standing-wave device (Garrett, 2004) and that since a travelling-wave device is based on the Stirling cycle it can theoretically achieve Carnot efficiency.

Assessment of Fisher et al. (1994): Prototype thermoacoustic refrigerators had been built and tested with reported low levels of efficiency relative to conventional vapor compression technology; however, they noted there were no fundamental reasons why the efficiency levels could not be improved with sufficient development. However, their overall assessment was that thermoacoustic refrigerators held little promise for replacing vapor compression equipment, with commercialization prior to 2000 being unlikely. They further noted that extensive effort was needed: (1) to address the constraint imposed by the resonator on the size of the external heat exchangers, (2) to address the likelihood of shocks waves being created, and (3) to develop acoustic compressors.

Advancements and State of Technology: While Minner *et al.* (1997) predicted a COP = 1.7 for a thermoacoustic refrigerator, which was comparable to conventional household refrigerators of that time, the measured Second Law efficiency for prototypes has typically ranged from about 0.1 to 0.2 (Paek *et al.*, 2007), which is significantly below contemporary vapor compression values, which range from about 0.3 to 0.5.

Much early development work was based at Los Alamos Laboratory, with much follow on work being performed at Purdue University and Penn State University. In 2004, Professor Garrett of Penn State University created a consulting company (ThermoAcoustics Corporation) dedicated to thermoacoustics, which developed thermoacoustic cycle-based working prototypes for NASA, the U.S. Navy, and Ben & Jerry’s (an ice cream manufacturer), with some commercial promise (see, for example, Smith (2004)). However, based on our review, we are led to believe that none of these projects currently is being actively pursued.

Continuing issues with prototypes include, among others, low cooling capacities, large physical size, heat exchanger inefficiencies, and heat conduction from the hot heat exchanger to the cold heat exchanger.

Overall Assessment: For the next twenty year period, our assessment is that it is likely that thermoacoustic cooling will remain uncompetitive with vapor compression technology, but will likely continue to be a topic of research interest. For example, while not commercially viable, Zink *et al.* (2010) considered for automotive applications a thermoacoustic engine which could be powered by engine exhaust and used to drive a thermoacoustic air conditioning system. While outside the scope of this paper, much interest is being shown in thermoacoustically driven pulse tube cryocoolers because of their reliability and overall size.

3.2.4 Other Leading Alternative Cooling Options

None of the other alternative cooling options appear poised to replace vapor compression technology; however, they are important because of their uses in niche applications and their increasing market penetrations due to increasing environmental concerns.

Absorption and adsorption: Over the next twenty years, our assessment is that research and development of these technologies will continue; however, they will retain a small share in most markets unless the cost of energy significantly increases. These systems will continue to be used and will expand into applications where management of peak electricity demand is important, where sources of waste heat are readily available, and in solar applications.

Desiccant: Over the next twenty years, our assessment is that it is likely that the overall market penetration of desiccant cooling systems will remain low; however, research and development will continue in the areas of solid and liquid desiccant materials, improving cycle performance, reducing maintenance issues, and reducing costs. The most likely continued use of desiccant based systems will be to manage latent loads in high humidity areas while being coupled with smaller-sized, conventional vapor compression technology to manage the sensible loads.

Thermoelectric Cooling: Over the next twenty years, our assessment is that it is likely that thermoelectric cooling will remain uncompetitive with vapor compression technology other than in certain niche applications with low cooling requirements and modest temperature lifts, e.g., certain electronic cooling applications, certain military and space applications, certain medical applications and recreational cooling, where the simplicity of the cooling system is an important asset and outweighs the low efficiency of this technology.

Transcritical CO_2: Over the next twenty years, our assessment is that it is likely that the transcritical CO_2 cycle will continue to be an area of continued research interest with possible larger scale commercial introduction, which would reduce the system costs to a more competitive level. If large scale commercialization is realized, it is likely to be for small capacity applications due to the large volumetric cooling capacity of CO_2. Moreover, the transcritical CO_2 cycle will likely expand in niche applications (e.g., heat pump water heaters). However, for the transcritical CO_2 cycle to be more widely applied, it is likely that outside factors (e.g., taxes, regulations, legislation, public perception, etc.) will need to come into play. Some issues that still need to be addressed are: costs, safety, maintenance, and efficiency at high ambient temperatures.

4. CONCLUSIONS

We reviewed the state-of-the-art of alternative cooling and near-room temperature refrigeration technologies using as a starting point the assessment of these technologies by Fisher *et al* (1994). Among the new technologies studied, since 1994 only the transcritical CO_2 cycle has entered the commercial market to date, primarily for water heating and commercial refrigeration, though its market share remains small. The progress in the commercial development of most of the other new technologies since 1994 has been much lower than the predictions made by experts working on the respective technologies. Magnetic refrigeration has the highest level of research activity and promise for implementation; however, several technical breakthroughs are needed to realize this promise. The attractiveness of absorption, a “conventional” alternative technology, is increasing because of its capability to utilize waste heat, which improves the life-cycle economics of this equipment compared to vapor compression machines.

In conclusion, we expect different cooling technologies to find increased market application, particularly niche ones. However, we do not foresee any of these technologies achieving widespread displacement of the vapor compression technology in the immediate future because of their low energy efficiency or high cost, or both. Significant technical breakthroughs are needed to advance the market prospect of novel cooling concepts. One goal of a recent $30 million funding package (ARPA-E, 2010) is to accelerate commercial implementation of these systems.

5. NOMENCLATURE

COP	Coefficient of Performance
SEER	Seasonal Energy Efficiency Ratio
T	temperature, °C or K
Greek	
ΔT_L	$= T_L - T_{evap}$, K
ΔT_H	$= T_{cond} - T_H$, K
Φ	Second Law Efficiency, eq. (1)

Subscripts	
Carnot	Carnot cycle
cond	condenser
evap	evaporator
H	high temperature reservoir
L	low temperature reservoir

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