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Review of alternative cooling technologies

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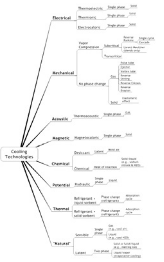
HIGHLIGHTS

- We reviewed the state-of-the-art of alternative cooling technologies.
- Progress in developments has been lower than predicted in 1994.
- Likely to find increased niche market applications in the future.
- Unlikely to widely displace vapor compression technology in the near-term future.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper provides an update on alternative cooling technologies in the context of a report by Fischer et al. [2], which contains an extensive assessment of "not-in-kind" technologies including their state-of-the-art, development issues, and potentials to replace vapor compression equipment. After nearly 20 years, it is now of interest to update the status of alternative technologies considering regulatory actions aimed at refrigerants with high global warming potential. Several technologies are considered with sorption cooling, desiccant cooling, magnetic cooling, thermoacoustic cooling, thermoelectric cooling, and transcritical CO_2 being discussed in some detail. For each technology we present its physical principle, a brief summary of the findings of Fischer et al., the technological advancements since their study leading to the current state-of-the-art, and our assessment as to the potential of each technology to enter the market as a supplement to or replacement of vapor compression equipment in the next 20 year period.

1. Introduction

Vapor compression air-conditioning and refrigeration equipment dominates the market for residential and commercial buildings. For example, greater than 99.9% of all units shipped in the United States in 2005 were based on this electrically-driven technology [1]. This dominant position of vapor compression equipment has been achieved due to its low first cost, superior efficiency (low operating cost), and good personal safety record. However, the most commonly used refrigerants, halogenated alkanes, have been implicated as contributing to destruction of stratospheric ozone and global climate change, which has necessitated an examination of different cooling technology options.

One of the most thorough studies on alternative cooling options was performed by Fischer et al. [2]. They investigated ten alternatives that were emerging or were being developed at the time of their report, and which they believed were potentially able to replace vapor compression technology, thus eliminating the need for chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) refrigerants. In addition to their study, three other reports [3–5] are not as broad but worth noting. While implementing refrigerants with zero ozone depletion potential (ODP) was the main industry objective in the 1990s, the current primary goal is the identification

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Nomenclature

COP	Coefficient of Performance (first law-based efficiency for thermodynamic refrigerators and heat pumps)
I	irreversibility, kJ
Q	heat transfer, kJ
SEER	Seasonal Energy Efficiency Ratio
T	temperature, °C or K
TEWI	Total Equivalent Warming Impact
W	work, kJ
Z	figure of merit, 1/K

Greek

ΔT_L	$= T_L - T_{evap}$, °C or K
ΔT_H	$= T_{cond} - T_H$, °C or K
Φ	exergetic efficiency, Eq. (1) (combined First and Second Law-based efficiency)
η	thermal efficiency (a First Law-based efficiency for heat engines)
ζ	$= \eta$ COP, energetic efficiency, Eq. (1) (First Law-based efficiency)

Subscripts

Carnot	Carnot cycle
cond	condenser
evap	evaporator
H	high-temperature reservoir
HE	heat engine
int	internal to cycle
L	low-temperature reservoir
o	reference
R	refrigerator or heat pump
tot	total

and introduction of high efficiency, low global warming potential (GWP) fluids to minimize both the direct and indirect effects of air-conditioning and refrigeration equipment on the earth's climate. The need for high efficiency systems cannot be overemphasized because the majority of electrical energy is produced from the burning of fossil fuels, and the amount of energy consumed for space cooling and refrigeration 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 [1]. Given increasing primary energy costs, the unequal distribution of primary energy reserves in the world, political instabilities throughout the world, and the increasing awareness by the current generation of its responsibility to use primary energy reserves in a sustainable manner — to mention only a few issues and concerns—it is increasingly incumbent upon the industry to continuously improve the energy efficiencies of its systems.

In light of the above discussion, it is worthwhile periodically to review the status of alternative technologies and readdress the question of whether or not these technologies have been developed to the point of being able to compete with and replace, at least in part, vapor compression technology. In developing our update on alternative technologies, we believe it is important to report not only on the current state-of-the-art but also on the technological progress achieved over a well-defined time frame, as the rate of progress can be an useful indicator of the feasibility of reaching a competitive status for a given technology. For this reason we opted to use the findings of Fischer et al. [2] as the "marker" from which the realized technical advancements are reported. While acceptance of a given technology in the market is dependent on its being able to satisfy a variety of criteria, e.g., cost, physical size, weight, manufacturability, serviceability, reliability, safety, environmental impact, availability of the primary energy source, among many other, this update on the state-of-the-art, similar to [2], focuses on efficiency as the chief parameter indicating the market potential of different technologies during preliminary screening.

This paper considers several technologies. Sorption cooling, desiccant cooling, magnetic cooling, thermoacoustic cooling, thermoelectric cooling, and transcritical CO_2 being discussed in some detail. For each technology the paper presents the physical principle, a brief summary of the findings of Fischer et al. [2], the technological advancements since the 1994 study leading to the current state-of-the-art, and our assessment as to the potential of each of the technologies to reach market viability and compete with vapor compression equipment for space cooling and near-room temperature refrigeration in the next twenty year period. Given the breadth of the topic and editorial prerogatives necessitated by space limitations, the coverage of individual technologies is limited. For the same reason, this paper reports only the key findings and cites just a few publications out of over 100 reviewed. A complete list of references is available from the authors.

2. Considerations for objective performance comparison

2.1. Technical merits of exergetic efficiency

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 for a given capacity and source and sink temperatures. The most common performance measure for these systems is a First Law-based efficiency, namely, the Coefficient of Performance (COP). However, the typical definition of COP is less helpful when the primary energy input is not a form of work (mechanical, electrical, …). To make this point clearer, consider that work requiring and work producing energy systems can be broadly classified into refrigerators/heat pumps and heat engines, and that First Law-based efficiencies can be thought of as measures of "how well energy is used", that is, they can be thought of as ratios of "energy output to energy input". As an example of the first type of energy system mentioned above, the refrigeration system of Fig. 1a typically has a First Law-based efficiency defined as $COP = Q_{L,R}/W_R$. As an example of the second type of energy system mentioned above, the heat engine (produces mechanical work from thermal energy) of Fig. 1b typically has a First Law-based efficiency defined as $\eta = W_{HE}/Q_{H,HE}$. However, neither of these measures is sufficient when the primary energy input for a refrigeration system is thermal energy, such as is shown in Fig. 1c. In this case, the First Law-based efficiency is a combination of η and COP, namely, $\zeta = \eta\ COP = Q_{L,R}/Q_{H,HE}$.

Regardless of the type of refrigeration system, comparing alternatives—or even the same system—solely based on First Law-based efficiencies can be misleading or incomplete. For example, what if the cooling capacity is not fixed and/or the source and sink temperatures are not fixed? In these cases, would a COP or ζ of 5 be better than 4? Not necessarily!

Therefore, in addition to performance indexes based on the First Law of Thermodynamics, it is appropriate to compare different systems, or even the same system operating under different conditions, using performance indexes based on both the First and Second Laws of Thermodynamics, which compare the actual performance to the ideal (Carnot) performance, such as the ones