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Energy-efficient and -economic technologies for air conditioning with vapor compression refrigeration: A comprehensive review

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HIGHLIGHTS

- Advanced technologies are reviewed for vapor compression refrigeration systems.
- The technologies include radiative cooling, energy storage and defrosting.
- Heat pump, desiccant dehumidification and heat recovery are also covered.
- Each technology is introduced with mechanisms, advantages and future work.
- This review gives a big picture for energy-efficient and -economic cooling.

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ABSTRACT

Vapor Compression Refrigeration Systems (VCRS) are widely used to provide cooling or freezing for domestic/office buildings, supermarkets, data centres, etc., which expend 15% of globally electricity and contribute to ~10% of greenhouse gas emissions globally. It is reported that cooling demand is expected to grow tenfold by 2050. Therefore, it is critical to improve the efficiency of the VCRS. In this paper, a comprehensive review of advanced and hot technologies is conducted for the VCRS. These technologies include radiative cooling, cold energy storage, defrosting and frost-free, temperature and humidity independent control (THIC), ground source heat pump (GSHP), refrigerant subcooling, and condensing heat recovery. Radiative cooling could produce a cold source ~8 °C lower than the surroundings, which reduces the electricity consumption of the VCRS by ~21%; cold energy storage is used to shift the peak cooling load, and as a result, the electricity consumption and operation cost of the VCRS could be reduced by ~12% and ~32%, respectively; frosting is a big issue of the VCRS especially for freezing applications, and more than 60% of electricity consumption for defrosting could be saved with the advanced defrosting and frost-free technologies; THIC deals with the building sensible load and latent load separately, which not only increases the COP of the VCRS by ~35%, but also improves the building thermal comfort; GSHP uses the ground as a low-temperature cooling source for condensing the refrigerant in the VCRS in summer, which decreases the condensing temperature by ~5 °C and correspondingly increases the COP of the VCRS by ~14%; refrigerant subcooling and condensing heat recovery can increase the refrigerating capacity and achieve multi-functions of the VCRS, respectively. The review is summarized in terms of the technology classification, basic ideas, advantages/disadvantages, current research status and efforts to be made in the future.

1. Introduction

The refrigeration system plays an indispensable role in many areas, such as residential or commercial buildings, industry, cold chains, etc. It provides thermal comfort for buildings, keeps food or medicine at desired temperatures, and is essential for some industrial processes as

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Nomenclature

AC	air conditioning
COP	coefficient of performance
ED	electrodialysis
GSHP	ground source heat pump
Le	lewis
MPCMs	microencapsulated phase change materials
NTU	number of transfer unit
PCMs	phase change materials
TES	thermal energy storage
THIC	temperature and humidity independent control
VCRS	vapor compression refrigeration system

well, such as air liquefaction. With the increase of population and development of urbanization, the demand for cooling increases significantly, which is reported to grow tenfold by 2050 [1]. Hence, the increase of energy consumption of refrigeration systems is expected. However, according to the annual energy outlook 2017 (with projections to 2050) [2], it is found that energy consumption of refrigeration and cooling, in both residential and commercial sectors, remains relatively flat or decline slightly from 2016 to 2040, as shown in Fig. 1, despite the growth in the number of households and the amount of commercial floor space. This is mainly due to the improved refrigeration efficiencies by the use of advanced technologies.

Up to now, Vapor Compression Refrigeration System (VCRS) is the most popular and widely used refrigeration system, which has a market share of 80%. Therefore, it is critical to improve the efficiency of the VCRS for decreasing the energy consumption of refrigeration. As a matter of fact, relevant technologies have been investigated since early last century and some of them have been widely applied in the VCRS. These technologies include radiative cooling, cold energy storage, defrosting and frost-free, temperature and humidity independent control (THIC), ground source heat pump (GSHP), refrigerant subcooling, and condensing heat recovery.

The radiative cooling technology is based on the mechanism that a body at typical ambient temperatures can radiate heat into the colder outer space at 273 K, which cools down the body's temperature and achieves cooling effect. Vall and Castell [3] made a review on radiative cooling consisting of backgrounds, theoretical approaches, numerical simulations and prototypes, but they did not discuss the potential of the radiative cooling for improving the VCRS performance.

The basic idea of the cold energy storage technology is to generate cold energy at off-peak times, store it with energy storage media, and then release it at peak times. It can not only save energy by storing excess cold energy of the VCRS, but also reduce the operation cost due to the cheap off-peak electricity. Moreno et al. [4] conducted a review of thermal energy storage of heat pumps for building cooling and heating, using phase change materials (PCMs) as the energy storage media.

Frost formation is inevitable in the VCRS when surface temperature of heat exchangers is below 0 °C. On the one hand, frosting significantly decreases the operating efficiency of the VCRS due to the increased thermal resistance. On the other hand, it consumes large amounts of energy for defrosting. Therefore, energy-efficient defrosting or frost-free technologies are required. Wang et al. [5] presented a review of anti-frosting technologies in refrigeration and air conditioning fields, with an emphasis on the surface treatment technology.

The THIC deals with the sensible load and latent load of air conditioning individually: the latent load is processed by liquid or solid desiccant dehumidification; the sensible load could be processed by the VCRS with a much higher evaporating temperature at ~15 °C (traditionally it is ~5 °C), which significantly improves the performance of the VCRS. Giampieri et al. [6] reviewed the working principle of liquid desiccant systems, focusing on the thermodynamic properties of the desiccant solutions to identify which thermodynamic property influences the liquid desiccant process. Sultan et al. [7] made a review on the solid desiccant air conditioning system and comparisons were made with the conventional vapor compression air conditioning system.

Ground source heat pump (GSHP) for cooling relies on the fact that the ground has a lower temperature than the air in summer. Therefore, the ground could work as a low-temperature cooling source for condensing the refrigerant in the VCRS and hence increase the system performance. Lucia et al. [8] made a review on the GSHP systems with first and second law thermodynamic approaches for modeling. However, they only covered the horizontal and vertical ground heat exchangers without the pile foundation ground heat exchanger.

In the VCRS, subcooling the refrigerant at the inlet of the expansion

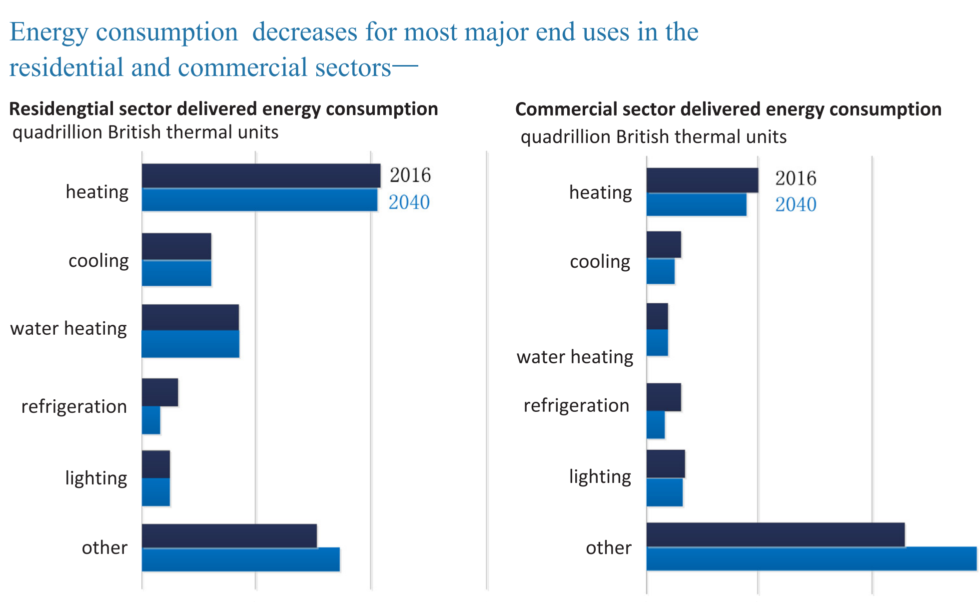

Fig. 1. Residential and commercial sectors delivered energy consumption [2].