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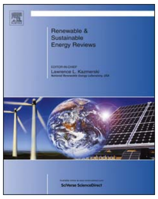

A review of regenerative heat exchange methods for various cooling technologies

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ABSTRACT

Regenerative heat exchange method internally recovers useful cooling and heating energy inside a closed-loop cooling system. However, depending on the specific cooling mechanisms for various cooling technologies, the configurations and characteristics of regeneration methods diverge significantly. Therefore, it is necessary to review the fundamental principles and clarify the common features and major differences of the regeneration methods for various typical cooling technologies. This study classified regeneration methods into three categories: recuperative type for steady state operated systems, regenerative type for systems under cyclic operation, and heat recovery type for systems with solid-state functional materials. The first group of regeneration methods are recuperative heat exchangers, transferring heat continuously between two streams of fluid with different inlet temperatures to pre-cool one stream and enhance the cooling power, such as the suction-line heat exchanger for vapor compression systems. The second group of regeneration methods are regenerative heat exchangers, which fundamentally are energy storage devices to cyclically transfer heat from gaseous refrigerant flowing through them. The third group of regeneration methods are internal heat recovery processes, wherein fluid is applied as a regenerator to store/release thermal energy cyclically to pre-cool and pre-heat the solid-state functional materials. For each of the three regeneration methods, their physical principles, a summary of their state-of-the-art development status, and assessments of their advantages, limitations and unique features are presented.

1. Introduction

Vapor compression based HVAC and refrigeration systems have dominated the market for a long time. Unfortunately, the use of conventional Freon refrigerants in vapor compression cooling systems has caused the ozone depletion crisis and exaggerated the global warming and climate change nowadays [1]. To build an environmentally friendly future, therefore, alternative cooling technologies have been developed during the past few decades to reduce the use of environmentally harmful conventional refrigerants. These alternatives include solid-state cooling technologies such as thermoelectric cooling [2], magnetocaloric cooling [3], electrocaloric cooling [4] and elastocaloric cooling [5]. In addition, heat activated cooling technologies also regained research attentions due to their capabilities to utilize renewable energy including solar/waste heat and geothermal energy, such as absorption cooling [6] and adsorption cooling [7,8] technologies. Another example of renewable energy utilization is the air (ground)-source heat pump. Based on vapor compression cycle, it absorbs renewable thermal energy from air or underground soil and rejects it to provide space heating or domestic hot water, which is superior to conventional electric heating from energy efficiency perspective [9]. To bring these alternatives competitive to the conventional vapor compression cooling systems, the first issue to solve is the energy efficiency. Unfortunately, most of these alternative cooling technologies are still suffering from relative low efficiency performance due to significant losses in their systems, since there are many factors that are not optimized yet.

One of the most important key factors contributing to low efficiency for some of these alternatives is lack of or low efficient internal regenerative heat exchange. This is critical for some of the novel solid-state cooling technologies, wherein no regeneration was applied at all [4,10,11], since the scientists constructing demonstration prototypes are either not aware of this concept or not familiar with the heat exchange physics of regeneration, leading to either lack of regeneration or poor regenerative heat exchange performance. For some more matured technology, such as adsorption cooling, the ideal regenerative heat exchange process and its realistic variations as a compromise between performance and system cost/complexity are still under

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Nomenclature

AMR	active magnetocaloric regenerator
Bi	Biot number [-]
COP	coefficient of performance [-]
c_p	specific heat [J kg^{-1} K^{-1}]
EC	electrocaloric
G-M	Gifford-McMahon
HR	heat recovery
HTF	heat transfer fluid
HX	heat exchanger
h	convective heat transfer coefficient [W m^{-2} K^{-1}]
k	thermal conductivity [W m^{-1} K^{-1}]
MC	magnetocaloric cooling
L	latent heat or mass based energy density [J kg^{-1}]
NTU	number of transfer unit [-]
PTR	pulse-tube refrigerator
SHX	solution heat exchanger
SLHX	suction-line heat exchanger
T_c	heat source temperature (low temperature side of heat pump) [K]
T_g	generator temperature (for heat driven cooling technologies) [K]
T_h	heat sink temperature (high temperature side of heat pump) [K]
ΔT_{span}	temperature span of the regeneration method [K]
U	overall heat transfer coefficient [W m^{-2} K^{-1}]
α	ratio between the dead thermal mass of parasitic parts and the working material [-]
β	heat exchange surface area density [m^2 m^{-3}]
γ	non-dimensional latent heat [-] defined in Eq. (1)
ε	effectiveness [-]

discussion for development [12]. In addition, all these cooling (heat pump) technologies are based on different cooling mechanism, resulting in various regeneration methods in entirely different forms. Understanding the operating principle and the state-of-the-art is prerequisite for performance improvement. Unfortunately, some of these regeneration methods are not intuitive to understand, because some are simple heat exchangers, and some are more complicated sequences of heat exchange processes (heat recovery processes). Given the above three facts, a comprehensive review of regenerative heat exchange methods for current available cooling technologies is necessary to guide the development and improvement of the alternative cooling technologies. Comparison brings new opportunities. After reviewing the state-of-the-art of each regeneration methods, a comparison of their similarities and major differences (unique features) between them are presented. Furthermore, design experiences and lessons of regenerative heat exchange methods from more developed cooling systems may lead future research and development for less developed cooling systems, especially for new solid-state cooling technologies. Finally, this review is intended for a broader audience, especially for research scientists with materials or physics background, to better develop current and future novel cooling technologies.

To the best of our knowledge, regenerative heat exchange methods for HVAC and refrigeration industry have been applied for both open-loop air systems and closed-loop refrigerant systems, as indicated by Fig. 1. In open-loop air systems, heat recovery (HR) has been widely adopted to precool (pre-dehumidify) processing air in summer and preheat processing air in winter by enthalpy wheels [13–15]. Similarly, in closed-loop cooling and refrigeration systems, the concept of better utilization of available heating/cooling energy inside systems via advanced cycle and process design, has been applied in all kinds of cooling systems to enhance system performance. This feature has been known as recuperative heat exchangers or regenerators for different applications and systems, wherein more useful cooling can be recovered instead of being wasted. In this paper, for various closed-loop cooling and refrigeration systems, the terminology "regenerative heat exchange" or "regeneration" refers to the internal heat exchange equipment or process between two working substances at different temperatures to precool and preheat each other. To differentiate them, we classified regeneration methods used in various cooling systems into three groups, as demonstrated in Fig. 1. The first "recuperators" group is corresponding to cooling systems operated under steady state condition. The second "regenerators" have been used in cyclically operated systems with gaseous working fluid, while the third "cyclic heat recovery" is for cooling systems operated cyclically with solid-state functioning materials. Among them, we found particularly that regeneration is indispensable for all cryogenic cooling technologies, and therefore decided to include regenerative heat exchange methods for cryogenic cooling technologies as well, to find the common and unique features among various technologies from a broader perspective. In fact, the regenerator matrix configuration to achieve large heat transfer area can be applied to new solid-state cooling technologies for HVAC and refrigeration applications. In addition, from theoretical point of view, regeneration is essential to cryogenic cooling systems due to large required temperature span. As will be shown later in this article, the link between required temperature span and cooling energy density is a universal non-dimensional metric to determine whether or not regen-

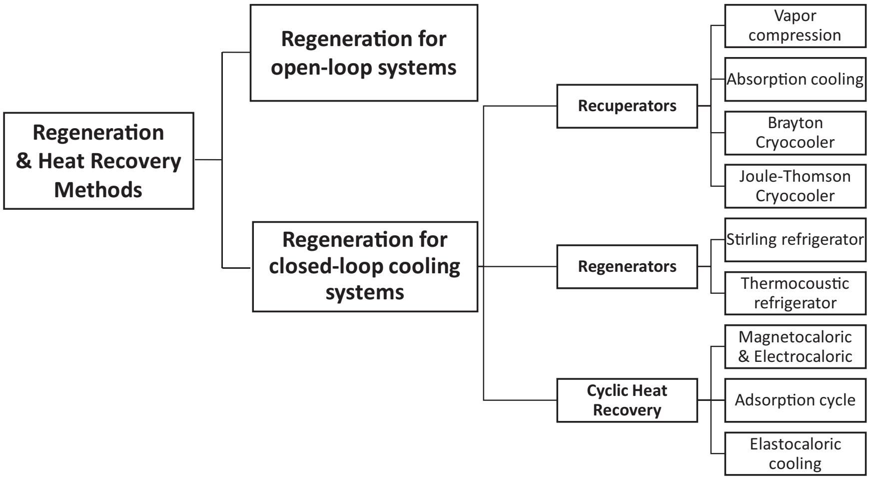

Fig. 1. List of various cooling technologies and their regeneration methods.