Chapter 1

Introductory Chapter: A Brief Note on Advanced Cooling Technologies

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Additional information is available at the end of the chapter

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1. Introduction

The smaller and faster based modern trend of manufacturing devices and equipment leads to dramatic increase in heat generation resulting in their higher failure rate and shorter longevity. For instance, the reduction of size of high-tech electronic devices and huge increase in the number of integrated components and subsequent increase in power density yielded enormous challenges for their fast and adequate cooling [1]. Since conventional cooling techniques are falling short in dealing with such high cooling demand, advanced and innovative cooling technologies are needed to meet the raising cooling demand of those modern devices, systems, and processes. In recent years, research and development in advanced cooling technologies as well as search for superior coolants have attracted tremendous interest worldwide and good progress has been made as numbers of new cooling systems as well as few new coolants have emerged [2, 3]. Recently, a feature on cooling technologies was published in technology report of BBC News where cooling technologies were also identified to be a red-hot sector [4]. While there is an urgent need to reduce (cool down) the global warming, the increasing cooling needs from modern devices, systems, and appliances as well as human comfort (like district heating and cooling) to be met with the advanced cooling technologies and coolants.

This chapter aims to provide a short note on advanced cooling technologies and emerging coolants as well as summarizing the key features and findings from each contributed chapter of this book.

2. Cooling technologies and emerging coolants

2.1. Cooling technologies

In order to employ cooling technologies for cooling any devices, components, equipment, process, appliance, or even space (rooms, buildings, etc.) for human comfort, it is necessary to understand the types of cooling technologies and their working mechanisms, capability, limitations, and other key information as well. Since most of these technologies are well established and explained in the literature and text books (e.g., [5, 6]), they will not be elaborated further here. However, based on energy input, a classification schematic of main cooling technologies and their subclasses is provided in **Figure 1**. It is noted that the cooling technologies can also be classified based on other factors such as coolants, and devices or systems to be cooled as well as direct or indirect cooling. For instance, depending on thermal load (heat flux), cooling methods, particularly for electronic devices and equipment, can generally be classified as follows:

- natural convection with air;
- forced convection with air;
- forced circulation of water;
- immersion cooling with natural convection;
- immersion cooling with boiling;
- heat pipe; and
- mini- or microchannel heat sinks (with liquid).

The selection of a cooling technique mostly depends on the heat generation by the equipment and the maximum heat transfer capacity of the method as well as their suitability. In general, natural convection is used where the heat dissipation is low, whereas for very high heat loads like in super computers and high heat-generating communication equipment, immersion cooling needs to be employed. For example, the generated heat flux of electronic components used in high-power microwave equipment such as radars can be as high as 2000 W/cm^2 and such components cannot be cooled by any cooling technique other than immersion of such components in suitable dielectric liquid where heat is removed by boiling [6]. Even in forced convection, the heat dissipation capacity of air is much lower than that of water. The possible heat flux that can be met at various temperature differences by different cooling techniques is provided in **Figure 2**. Based on heat flux (exact or range) and maximum allowable temperature for the component or device, the selection of cooling technique can be made by using the chart given in **Figure 2**. Like, for a heat flux of 0.1 W/cm^2 and allowable temperature difference of 60°C, natural convection with radiation can be considered, whereas for a heat flux of 1 W/cm^2, forced convection will lead to more than 100°C temperature rise and so immersion with fluorocarbons can be considered [6]. In principle, for larger heat fluxes, either forced water cooling or immersion with boiling are the choices.

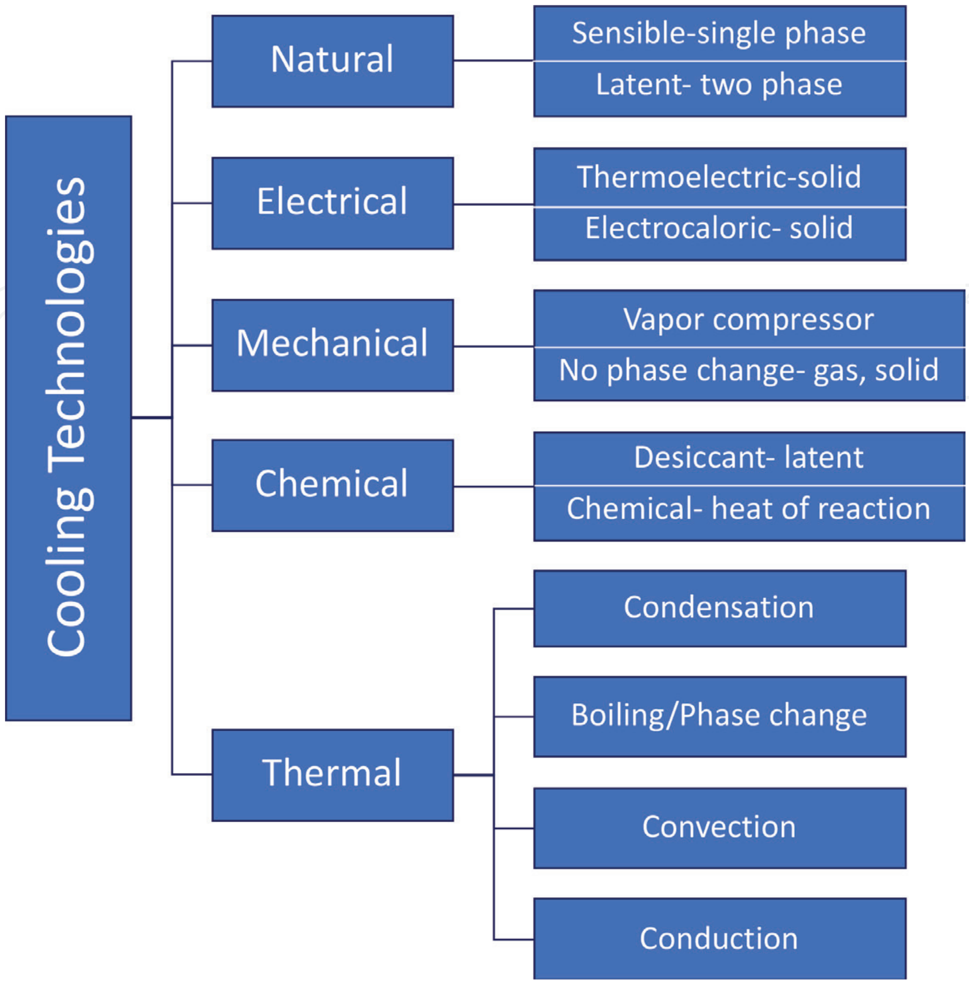

Figure 1. Schematic classification of cooling technologies based on energy input.

Recent review and analysis on the cooling technologies by the author revealed that micro-channel-based forced convection and phase-change (like heat pipe) cooling are among the most promising techniques that are suitable and capable of removing very high heat loads [2]. However, because of very compact, lightweight, and superior convective cooling performance (for microscale hydraulic diameter of the channel), extensive research works have been performed on the application of microchannel-based cooling systems (e.g., heat sinks) in cooling high heat-generating devices [7–9]. Although heat pipes are already used commercially and have large market value, microchannel-based cooling technology is mostly in the development stage showing great prospect. Details about cooling technologies, their mechanisms, performance, and suitability for specific cooling need can be found in literatures [2, 5, 6] and will not be discussed here.

2.2. Emerging coolants

Although good progress has been made in the innovation and advancement of cooling techniques, very little advancement of coolants and coinage of new coolants have been made.

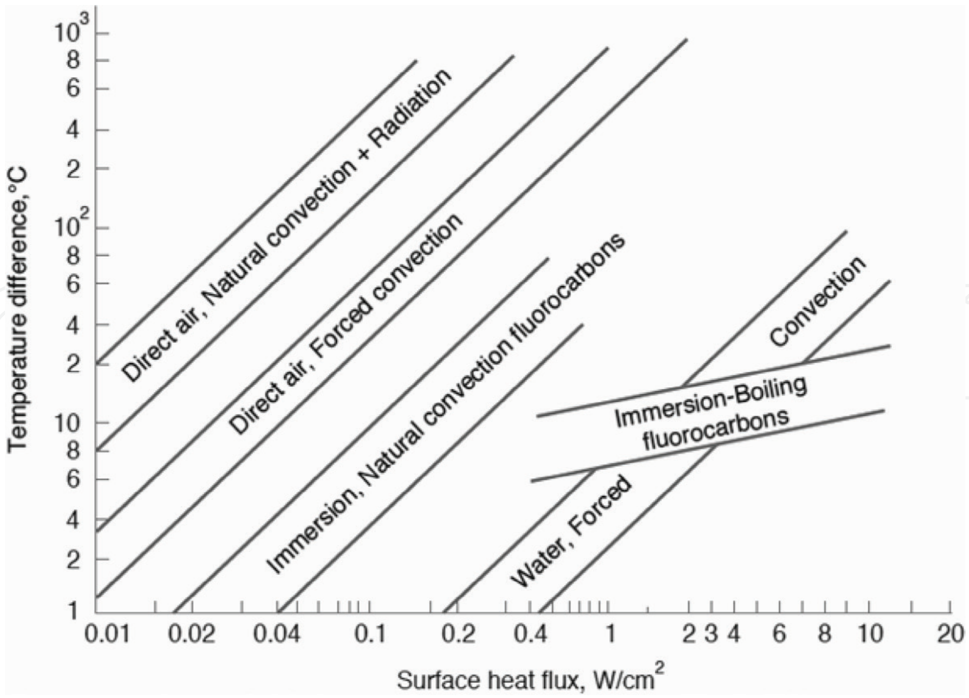

Figure 2. Cooling method for various heat flux and specified temperature differences [6].

This is mostly due to the limitation of improving cooling performance of conventional fluids without compromising other important factors. Nonetheless, there is always a need to have fluids with superior cooling capability compared to the conventional ones. Thus, researchers have long been trying to either develop new class of fluids or to improve the thermal properties of conventional heat transfer fluids.

Subsequently a new class of fluids termed—nanofluids, which are the suspensions of nanoparticles in conventional fluids, was coined in 1995 [10]. As a new type of engineered fluids (coolants), nanofluids exhibit mostly substantially higher heat transfer properties and features such as thermal conductivity, heat capacity, convective and boiling heat transfer compared to conventional fluids [11–15]. These affirm that nanofluids are better coolants compared to conventional fluids. In addition, number of research works (e.g., [3, 16–18]) have been made where nanofluids were directly employed in cooling systems of commercial electronic or computing devices to evaluate the cooling performance of these new fluids. The results of these studies were promising as nanofluids in those cooling systems resulted in better cooling performance as compared to conventional cooling fluids. However, despite great prospects and extensive research conducted on these new fluids, there are many controversial and inconclusive issues remained. Another new type of nanofluids named—ionanofluids, which are the suspensions of nanoparticles in ionic liquids, was recently devised by our group [19]. Primary findings showed that these new nanofluids also exhibit superior thermal properties and show potential compared to pure ionic liquids for cooling applications [19–22].

Nevertheless, these emerging liquid coolants still need to be carefully studied and assessed for their performance and sustainable applications in advanced cooling technologies.

3. Summarizing contributions

Except this short note, each chapter's contribution and findings have been briefly highlighted in this section.

In the first contribution, the authors Jin and coworkers presented a novel energy-saving and environmentally friendly air-conditioning method which is an indirect evaporative air cooling heat exchanger based on M-cycle. Besides experimental investigation on this heat exchange system, they developed a computational model to study the impacts of key parameters on its performance. The model showed a close agreement with the experimental findings. It was demonstrated that the inlet air conditions and the dimension of the air flow passages considerably influence the cooling effectiveness. They recommended that the air flow passages can be redesigned to create greater turbulence resulting in a larger heat transfer coefficient so that a lower thermal resistance can be achieved. Also, the geometry of this indirect evaporative heat exchanger with a smaller hydraulic diameter and a higher Nusselt number can positively impact its cooling performance.

Spray cooling is one of the effective cooling technologies for high heat flux removal requirement and this cooling technique from two aspects: the entire spray (spray level) and droplets (droplet level) is thoroughly reviewed by the authors Gao and Li. Here, cooling is achieved through different modes like convective heat transfer from the heated surface to the film flow, nucleate boiling, liquid conduction inside the film flow, and interfacial evaporation from the liquid film. For the spray level, they emphasized the cooling performance to spray property and some key properties involving spray characterization, nozzle positioning, phase change, and enhanced surface are also summarized. Discussion on the droplet level is focused on the impact of droplet flow on film flow, which is the key flow mechanism in spray cooling. Besides highlighting advantages and barriers of using spray cooling for engineering applications, recommendations for future work and on unresolved issues in spray cooling are also made.

Development and evaluation of a novel heat pump-based energy system particularly for cooling high-power LED lamps and also for waste heat recovery was demonstrated by Cen and coworkers. They proposed an integrated system for temperature control and heat recovery to operate in conjunction with an LED lamp. The integrated system, which consists of a heat pump in which the LED lamp itself operates as the heat pump evaporator, adopts an active method to simultaneously achieve waste heat recovery and LEDs cooling. A prototype of this energy system was developed, and experiments were conducted to determine the effect of several parameters, such as cooling water flow rate and LED power on the LED lead-frame temperature, compressor power consumption, and system performance. Findings of this study reveal that this novel cooling system can lead to significant energy savings.

Author Vinicius evaluated module architectures and units of photovoltaic (PV) cooling systems aiming to determine, select, and design a modular system which can be applied in a real-scale photovoltaic power plant (PVPP) to enhance the yields of electricity production. A detailed analysis of the regional climatic, geographic, and solar conditions, as well as construction, operational, and maintenance aspects of this modular architecture-based cooling system is also provided. There are three major types of photovoltaic cooling systems which are photovoltaic-thermal (PVT) liquid and air collectors, PV ventilated with heat recovery, and non-PVT systems. Due to higher rates of heat exchange between the cooling fluid and the PV module, it was concluded that the best design and arrangement of the cooling system are of the coil and multiple-channel types.

Boiling is one of the most leading cooling mechanisms, and a comprehensive experimental study on nucleate pool boiling performance of refrigerants R-134a and R-410A on a powder-coated heating surface is reported by Dewangan and coauthors. Effects of heat flux and coating parameters on boiling performance are determined, and results are very promising as the boiling heat transfer coefficient was found to enhance by 1.9 times that of the plain heating surface. Besides evaluating the performance, it also presents an empirical correlation for the prediction of boiling heat transfer coefficient of refrigerants.

Whether conventional or advanced, the ultimate goal of development of any cooling technique is to remove the heat from the devices, systems, or processes in real-world applications. Thus, last two contributions focused on specific and industrial applications of cooling technologies. Cryogen spray cooling (CSC), which is highly transient with short spurt duration (several tens of milliseconds), has successfully been implemented in laser dermatology such as the treatment of port wine stain. The contribution by Zhou and Chen presents a review of the progress of this CSC in laser surgery for the treatment of port wine stain, focusing on flashing spray mechanism, spray and thermal characteristics of droplets, dynamic heat transfer, and strategies of heat transfer enhancement. It is demonstrated that the cooling ability of CSC which can be increased through alternative cryogens, new nozzles, and hypobaric pressure method is essential to improve therapeutic outcome, especially for darkly pigmented human skin.

In the last contribution, water-based centrifugal compressor cooling systems for industrial applications is carefully studied and analyzed by Hanslik and Suess. They focused on natural refrigerants as R404A is no longer a viable option for commercial refrigeration applications. The analysis of the systems has shown that a self-contained unit with water-loop combined with a centrifugal compressor cooling system with water as refrigerant proves to make sense from an energetic point of view. The main factors that influence the efficiency are the evaporation and ambient temperatures and the process pressure of the compressor. A promising option is the combination of a carbon dioxide process with a chiller using water as refrigerant.

4. Conclusions

This chapter briefly discusses various aspects of cooling technologies and emerging coolants besides highlighting main research contribution and results from each contributed chapter of this book. It is demonstrated that selection of cooling technology needs to be based on various key factors and their combination like heat removal capacity, suitability, and sustainability. Besides new cooling technologies, innovation and development of noble coolants are also crucial to meet the ever-increasing cooling demand. This book covers a number of key topics related to advanced cooling approaches, their performance, and specific applications. Finally, the book is believed to be a useful reference source of information and guide to all class of people who are involved or interested in the areas of cooling technologies and their applications.

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