Heat Transfer Enhancement - A Brief Review of Literature in 2020 and Prospects

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Abstract:

This review provides a brief literature survey on enhanced heat transfer research published in the English language journals in 2020. A topic search containing either "heat transfer" or "heat transport" or "thermal transport" in the Web of Science resulted in over 28,000 papers published in 2020 and nearly 30% were relevant to heat transfer intensification, which indicates the importance and rapid development of heat transfer enhancement technologies. The chosen studies focus on various heat transfer enhancement research categorized into conduction, convection, radiation, boiling and condensation, energy storage, thermal management, and cross research involving two or more categories. Heat conduction papers are selected from the micro/nanoscale areas with a focus on interfacial phenomena. Important active, passive, and compound techniques for enhancing convective heat transfer are incorporated. Thermal radiation is concentrated on near-field radiation and solar energy. Heat transfer enhancement in boiling and condensation as well as in thermal energy storage, renewable and sustainable energy, and thermal management of electronics and high-end equipment is critical in many engineering applications. From the selected literature published in 2020, significant attempts have been made to research and development on heat transfer enhancement technology covering both conventional and emerging techniques. The prospects of the heat transfer enhancement research are reflected according to the literature survey. Research of innovative heat transfer enhancement techniques is immense, encompassing every aspect from understanding the fundamental theory and physical mechanisms of various heat transfer enhancement techniques to their applications. Research of emerging techniques using new interfacial materials, nanofluids, micro- and nano-structures, microchannels, and new compound enhancement techniques incorporating conventional and new techniques becomes popular. However, there are big challenges in understanding the mechanisms, engineering design methodology and applications with these emerging techniques. Many aspects are urgently needed to be investigated and developed to achieve systematic theory, mechanisms and design methodology for applications in thermal processes, energy storage, renewable energy, decarbonized heating and cooling and many industrial and civil sectors.

Keywords: Heat transfer, Enhancement, Energy storage, Solar energy, Phase change, Boiling, Condensation, Nanoscale, Interface, Thermal management, Heat exchanger, Device.

1. Introduction

Heat transfer enhancement (HTE) or augmentation or intensification means the improvement of thermal performance of any heat transfer process, heat exchanging medium, thermal component, heat transfer device, heating/cooling equipment, or thermodynamic system. Following the brief reviews conducted in the past (Guo, 2019; Guo et al., 2020) on heat transfer intensification literature, the present review continues to circumscribe the heat transfer augmentation papers published in archival journals in English language in the single year 2020. Considerable effort has been devoted to research on heat and mass transfer intensification and the publication amount is huge; thus, selection is unavoidable. Nevertheless, the authors tried to cover a wide range of areas related to the subject of enhanced heat transfer, namely active, passive and compound techniques in convective heat transfer, interfacial heat conduction, near-field radiation and solar energy, boiling and condensation heat transfer, energy storage, electronics thermal management, process heat transfer, and high-performance heat-exchange devices, etc.

A topic search in the Web of Science with keywords either "heat transfer" or "heat transport" or "thermal transport" conducted on April 5, 2021 returned 28,437 papers published and recorded in the database of the Web of Science in 2020. A further search refinement containing words either "enhancement", or "augmentation", or "intensification", or "enhanced", or "augmented", or "intensified" resulted in 8,429 papers relevant to enhanced heat transfer published in 2020, representing a ratio of 29.64% heat transfer augmentation to general heat transfer. Table 1 lists the yearly paper number data in heat transfer and heat transfer enhancement, respectively, acquired from such topic searches in the past two decades from 2001 to 2020. It also compares the yearly increase percentage rate as well as the paper percentage ratio of heat transfer enhancement among heat transfer research. The table shows that the publications on heat transfer and enhanced heat transfer are soaring year by year, though a slight declination was noticed in 2002, 2013, and 2020, respectively, as compared with prior year. The decrease in 2020 could be attributed to the delay of data recording in the database. The enhancement-related paper ratio is steadily increasing from a bit over 10% in 2001 to cross the line of 20% in 2015 and reaches nearly 30% in 2020. This indicates that the demand of research on enhanced heat transfer has been increasing. Certainly, heat transfer enhancement is now a crucial area of research and development in thermal management of data center, electronic cooling, energy storage and generation, power industry, manufacturing, building technology, transportation, aerospace and defense technologies, and many other engineering areas.

Table 1. Yearly number of papers on heat transfer and enhanced heat transfer indexed in the Web of Science in the past 20 years.

Year	HT*	HT yearly increase (%)	HTE**	HTE yearly increase (%)	HTE/HT (%)
2001	6716	7.56	800	12.99	11.91
2002	6659	-0.85	767	-4.13	11.52
2003	7449	11.86	904	17.86	12.14
2004	7907	6.15	971	7.41	12.28
2005	9193	16.26	1195	23.07	13.00
2006	9387	2.11	1225	2.51	13.05
2007	10399	10.78	1443	17.80	13.88
2008	11354	9.18	1665	15.38	14.66
2009	12744	12.24	1955	17.42	15.34
2010	13451	5.55	2158	10.38	16.04
2011	14257	5.99	2392	11.08	16.78
2012	16259	14.04	2974	24.33	18.29
2013	16004	-1.57	3014	1.34	18.83
2014	18597	16.20	3674	21.89	19.76
2015	19881	6.90	4031	9.71	20.28
2016	22651	13.93	5055	25.40	22.32
2017	25410	12.18	5922	17.15	23.30
2018	25553	0.56	6347	7.18	24.84
2019	28836	12.84	7601	19.76	26.36
2020	28437	-1.30	8429	10.89	29.64

*Topic search results containing keywords either “heat transfer” or “heat transport” or “thermal transport”.

**HT search results further containing keywords either “enhancement” or “augmentation” or “intensification” or “enhanced” or “augmented” or “intensified.

2. Heat Conduction

This section succinctly reviews the literature for heat conduction augmentation in the micro/nanoscale with a focus on nanoscale and interfacial heat transfer. The rapid development of modern technology demands heterogeneous integration at the micro/nanoscale to create advanced functionalities and manufacturing. An interface between dissimilar materials can impede or augment heat transfer due to mismatch or match of phonon transport spectra across the interface. In general, interface is an unwanted impediment to heat dissipation in a plethora of highly integrated electronics and high-power devices. On the other hand, nanostructured materials to obtain ultra-low thermal conductivity has proven to be extremely attractive for numerous applications such as thermoelectric energy conversion, thermal management and insulation. Therefore, interfacial thermal transport is leading to fundamental challenges for the design and implementation of advanced nanostructures for energy conversion, computation, and data storage, to name a few. The lattice thermal conductivity, particularly in semiconductors and insulators, is a key thermophysical property that determines the usability and functionality of advanced materials.

Lattice heat conduction can be modulated via nanostructure interfaces. Hu et al. (2020b) reported the machine-learning-optimized aperiodic superlattice for modulating phonon transport, the thermal conductivity of the GaAs/AlAs aperiodic superlattice is significantly lower than the periodic superlattice due to enhanced phonon localization. The aperiodic interference of coherent phonons gives a new way for controllability and understanding of phonon engineering to further suppress or enhance the thermal conductivities of various nanostructured materials. Another machine learning based work focusing on localization of phonons in Si/Ge aperiodic superlattices was reported by Chowdhury et al. (2020). The trend between thermal conductivity and randomness of multilayers was revealed - the scattering of incoherent phonons at interfaces is less, the room for randomization becomes less, and these put more coherent phonons out of Anderson localization and cause increased thermal conductivity.

Dai and Tian (2020) developed an anharmonic atomistic Green's function (AGF) model to incorporate anharmonicity at Si/Ge interfaces in three-dimensional structures rigorously, building in both harmonic and anharmonic first-principles force constants into the AGF without any fitting parameters. Huang and Guo (2020) used *ab initio* phonon Boltzmann transport equations to investigate lattice vibrational properties of diamond, c-BN, and Si. High thermal conductance across c-BN/diamond interface was reported, the interfacial thermal conductance of c-BN/diamond was ten-fold of Si/diamond; besides, the thermal conductance across Si/c-BN interface was 20.2% larger than that of Si/diamond at 300 K and 18.9% larger at 340 K. Wei et al. (2020b) announced significant enhancement of thermal boundary conductance in graphite/Al interface by ion intercalation; it was found that the phonon transmission from the intercalated graphite to Al significantly decreased with increasing Li-ion concentration. Wu et al. (2020b) investigated thermal conductance across graphene/MoS_2 van der Waals heterostructures via the first principles and molecular dynamics (MD) simulations. According to their calculations, the thermal conductance across the graphene/MoS_2 interface was 8.95 $MWm^{-2} K^{-1}$ at 300 K and the interfacial thermal conductance increased with temperature and the interface coupling strength.

Lee et al. (2020b) achieved a record-high thermal conductivity (101.7 $Wm^{-1}K^{-1}$) among soft isotropic thermal interface materials, mediated by the covalent bonding between hydroxyl groups of multiwalled carbon nanotubes (MWNTs) and ester groups of soft epoxy (SE) matrix. The solid interface was achieved by the coalescence between Ag flakes and Ag nanoparticles pre-functionalized on MWNTs (nAgMWNTs). The thermal conductivity in SE matrix was 11,300% greater than that in silicone rubber matrix. The soft isotropic nAgMWNT–Ag flake–SE thermal interface material showed good heat dissipation performance of a cellular phone application processor. Lu et al. (2020b) demonstrated the thermal conductance enhanced by atomic vacancies at Cu/Si interfaces, and used nonequilibrium MD simulations to determine the impact of interfacial atomic vacancies on thermal transport across a Cu/Si junction. In contrast to the reduction in thermal transport typically seen with bulk defects, the authors found that by introducing atomic vacancies at a concentration of 6.3% near the interface in either or both materials, the interfacial thermal conductance could be increased by up to 76%. Furthermore, the phonon density of states and normal mode decomposition revealed that the increase of interfacial thermal conductance originated primarily from optical phonons, supported by enhanced inelastic phonon transport which contributes to more than 60% of the increase.

Beardo et al. (2020) have detailed a multiscale hydrodynamic heat transport model that is able to predict frequency-domain thermoreflectance experimental measurements using *ab initio* calculated parameters. They tried to identify the resistive effects at the interface between a metal transducer and a silicon substrate. In contrast to previous interpretations based on an effective Fourier framework, by capturing the nonequilibrium effects induced by the interface and the nonhomogeneous heating, the model could reproduce both the amplitude of the temperature oscillations and the phase shift with the same set of geometry and frequency-independent coefficients. They found the hydrodynamic modes of thermal transport analogous to pressure- and shear-wave propagation in viscoelastic media. Bonomo et al. (2020) investigated the role of remote interface polar phonon modes on the electronic transport properties of dimensionally confined diamond structures. Their results showed that the hole scattering from remote polar phonons dominated, representing a fundamental contribution in the reduction of hole mobility and affording a more complete picture of the involved contributions. Sandell et al. (2020) compared three types of metal–polymer interfaces including Au/PMMA/Si, Au/Ti/PMMA/Si, and Au/Ni/PMMA/Si. They used the frequency-domain thermoreflectance technique to measure the effective thermal conductivity of the polymer film and then extracted the metal–polymer thermal boundary conductance.

The demand for polymers with high thermal conductivity is increasing due to their low density, low cost, flexibility, and good environmental resistance. In general, polymers have low thermal conductivity, and filling with high thermal conductivity nanofillers is a traditional method for enhancement of thermal conductivity. As Xu et al. (2000a) pointed out, however, increasing the intrinsic thermal conductivity of polymers is more paramount. Xu et al. (2000a) provided the first review on the mechanism of increasing polymer thermal conductivity by intrinsic structure tailoring: crystallinity, orientation of the crystallites, crystalline grain size, and alignment of the molecular chain in the amorphous region. Accurate thermal characterization methods were also reviewed for these structure-tailored polymers in low dimensions.

Wurtzite GaN, which has a wide band gap and can be epitaxially grown on diamond, is often used as the basic component in high-power electronics. Inherent to the growth of GaN-on-diamond devices, an epilayer layer is used to fabricate the GaN and diamond in order to obtain high-quality interface. Nanoscale epilayer placed between the GaN substance and the diamond cap facilitates growth of diamond on GaN and reduces the defects at the near-junction of heterostructure, which can contribute significantly to the overall thermal transport. Waller et al. (2020) implemented a weakly bonded interface model to predict the intrinsic interfacial resistance of GaN-on-diamond, with transient thermoreflectance measurements used for experimental confirmation. Without an interlayer, diamond only formed a weak van der Waals bond to GaN and the thermal boundary resistance was seven times higher than for GaN-on-diamond which included a silicon nitride interlayer, negating the heat spreading benefit of diamond. Therefore, a strong bond is crucial for the successful heterogeneous integration of GaN and diamond. Cheng et al.

(2020a) reported the temperature dependence of the measured interfacial thermal conductance of the room-temperature bonded GaN/diamond interfaces. They showed that the thermal boundary resistance in a 4.2 nm thick Si interlayer reached m^2KMW^{-1}, which was 74% lower than that in a 13 nm thick Si interlayer. Song et al. (2020a) examined the epilayer thickness effect through combining finite element simulation with calculation using a semi-classical phonon transport model. They found that with increasing GaN layer thickness, the device thermal resistance monotonically decreased until it reached a minimum at GaN thickness of ∼3.6 μm and GaN/diamond thickness of ∼5.8 μm.

The electrochemical intercalation of metal ions into layered materials is an innovative approach to actively and reversely regulate the thermal transport properties of layered materials. Field et al. (2020) concluded that replacing the amorphous interlayer with a higher thermal conductivity crystalline material would reduce the thermal boundary resistance of GaN-on-diamond devices. Diamond was directly grown onto an $Al_{0.32}Ga_{0.68}N$ interlayer integrated into a GaN/AlGaN device epitaxy. For the low Al content AlGaN interlayers, it was shown to be advantageous to include a SiC layer, which significantly improved heat transport from GaN to the diamond cap by avoiding defects near the interface.

In addition, interfacial thermal transport may involve multiple fundamental transport mechanisms, including inelastic phonon transport across the interface, and electron–phonon coupling in the metal and across the interface. Zhou et al. (2020b) quantified the impact of electron–phonon interactions on heat transport by using a modified transient thermal grating technique. The enhanced phonon scattering by photoexcited free carriers resulted in a substantial reduction in thermal conductivity on a nanosecond timescale. It provided direct experimental evidence of the elusive role of electron–phonon interaction in phonon heat transport, which is important for understanding heat conduction in doped semiconductors. Cheng et al. (2020b) provided a systematical benchmark study of interfacial thermal conductance across well-controlled epitaxial Al/sapphire interfaces. Their results showed that elastic phonon scattering dominated interfacial thermal transport, while inelastic phonon scattering and electron–phonon coupling had negligible effects. Oommen and Pisana (2020) showed that the insertion of a tantalum interlayer at the Al/Si and Al/sapphire interfaces strongly hindered the phonon transmission across these boundaries. The thickness-dependent thermal boundary conductance in Al/Si and Al/sapphire changed significantly within the initial few nanometers and reached saturation before ~5 nm on the addition of Ni and Ta interlayers. When the interlayer has a stronger electron–phonon coupling constant, the evolution of thermal boundary conductance is sooner.

Ma and Zhang (2020) studied the interface thermal conductance of $Cr_{0.22}Ni_{0.78}/MgO$ and $Cr_{0.22}Ni_{0.78}/Al_2O_3$ interfaces through the non-equilibrium MD simulation. They found that the thermal conductance enhanced by 3 and 2.4 times, respectively, by introducing an ultrathin Cu nano-interlayer. Ridley and Dyson (2020) addressed the phenomenon of mode-mixing in the acoustic and optical branches of the vibrational modes of III-V compounds, and its effect on the electron–phonon interaction. The valency-force-fields based model was employed to give a lattice dynamics description of the phenomenon of mode-mixing in the acoustic and optical branches of the vibrational modes of the diamond lattice. Evangeli et al. (2020) found that the interface thermal resistance decreased with increasing disorder in graphene/SiO_2 interface. The relative change of the momentum scattering rate increased with increasing disorder due to the increased electron–phonon scattering rate. It has been shown that disorder was important for electron cooling in graphene through disorder-assisted electron-phonon scattering, particularly via the super-collision process. This has direct implications for the performance of graphene interconnects for next-generation electronics.

3. Convection

Convective heat transfer enhancement is categorized into passive, active and compound techniques which cover solid surface modification, additional device, inserts, additives, functional fluids, external actions and combined methods. Emerging heat transfer enhancement techniques are fast developed due to the urgent needs for highly efficient heat transfer and zero-carbon technologies. Experimental investigations, numerical simulations and analyses of the heat transfer enhancement mechanisms have been conducted. Convective heat transfer enhancement in high-performance heat exchangers is of great practical significance for large-scale industrial applications including refrigeration, power plants, chemical processing and cooling of gas turbine and internal combustion engine.

3.1 Passive Techniques

3.1.1 Surface modification

Surface modification techniques here include use of extended surfaces or fins, treated surfaces and rough surfaces etc. Sharma et al. (2020) conducted experimental investigation on enhanced heat transfer and flow features in a duct mounted with various ribs of square, pentagonal, trapezium and truncated prismatic configurations and explained the fundamental heat transfer mechanisms according to the experimental results. Sadeghianjahromi et al. (2020) performed 3D turbulent flow numerical simulations to study heat transfer and flow friction characteristics of louver fin-and-tube heat exchangers and optimized the parameters of the heat exchangers. Chen et al. (2020b) experimentally investigated the heat transfer characteristics of gravity heat pipes with internal helical microfins in comparison with smooth gravity heat pipes. Kewalramani et al. (2020) conducted experimental and numerical studies on the thermohydraulic characteristics of heat sinks with short micro pin fin (height of fin shorter than the total height of heat sink) of different shapes (square and elliptical) and different arrangements (interrupted and staggered) using deionized water as the coolant. Boussoukaia et al. (2020) investigated the fractalization of convective flow upon vertical grooved disc/air interface under various uniform heat fluxes. Both the shadowgraph technique and image processing were employed to give a qualitative view of the development of these instabilities and quantitative measurements, respectively. Mitrovic (2020) conducted experimental studies on heat transfer and pressure drop during forced convection of air and liquid ethylene glycol in pipes with inner fins. The heat transfer coefficients of the finned tubes obtained with these liquids were higher by a factor of 3 to 8 compared to plain tubes, which was caused by efficient secondary flows between adjacent fins and interaction with the vortex core flow in the middle of the tube. Haridas et al. (2020) experimentally investigated the thermal performance of wavy channels under laminar flow conditions using a typical Mach-Zehnder interferometer and qualitatively and quantitatively analyzed the local and average profiles of the thermal boundary layer thickness and heat transfer rates. Abbas and Wang (2020) experimentally and numerically investigated the effect of fin displacement between alternate fins of plate-fin heat sink for heat transfer enhancement in cooling electronic devices under natural convection conditions. The effects of fin spacing, length, height, and heat flux on the heat sink performance subject to fin displacement were also studied. Kiwan et al. (2020) conducted an experimental investigation of the natural convection heat transfer from a vertical cylinder using porous fins under constant heat flux, steady-state and natural convection conditions; and clear enhancement of heat transfer using porous fins had been obtained. Akbarzadeh and Valipour (2020) conducted an experimental study on the heat transfer augmentation in nine different helically corrugated absorber tubes under the non-uniform heat flux. The thermal performance and heat transfer were considerably increased in the corrugated absorber tubes and the roughness height and pitch ratio had a significant effect on the performance. Hsieh et al. (2020) conducted experimental studies of heat transfer enhancement on a variety of roughened microchannels for a laminar flow at low Reynolds numbers with deionized water as the cooling fluid. Five different discrete roughened surfaces, which were circular, square, triangular, elliptical, and hexagonal in shape, were used in the test channels with a channel cross-sectional area aspect (height to width) ratio of 0.25. Zhou et al. (2020a) conducted experimental and numerical investigations on heat transfer enhancement by different shapes of micropillars of square (type A), circle (type B), fan-shaped (type C), drop-shaped (type D) and irregular drop-shaped (type E) embedded in microchannel heat exchangers. Higher thermal performance values were observed for type D and E micropillars, indicating better heat transfer performance of the microchannel heat exchangers under the test conditions. Li et al. (2020c) investigated heat transfer intensification, entropy generation and temperature uniformity analyses of shark-skin bionic modified microchannel heat sink. The flow structures and heat transfer characteristics of water-cooled microchannel heat sink modified by the proposed devices were investigated in laminar flow regime. Hassan et al. (2020) conducted a numerical study on the heat transfer enhancement and pressure drop inside deep dimpled tubes. The effects of the various configuration of dimples comprising three different pitches, diameters, and depths of dimples resulting in twenty-seven configurations were investigated. Zhang et al. (2020e) conducted experimental and numerical investigations of natural convection heat transfer of air in W-type fin arrays; and found that the air input was effectively increased in the direction perpendicular to the substrate, leading to smaller thermal resistance, while the intersection angle between the direction of velocity and the temperature gradient was reduced. Ho et al. (2020b) conducted an experimental study of two additively-manufactured metallic porous lattice heat exchangers for air-side heat transfer enhancement. These new porous lattice structures had enhanced the thermal performance of the heat exchanger with no penalty in pumping power. Lu et al. (2020a) numerically investigated the effects of surface roughness in microchannel with passive heat transfer enhancement structures of square channel, wavy channel and dimpled channel under laminar flow and heat transfer conditions. Li et al. (2020b) proposed to arrange the winglets radiantly around the tubes on the fin to enhance the airside heat transfer in fin-and-tube heat exchanger. The airside flow and heat transfer characteristics were numerically investigated and the position and the geometric dimensions of the vortex generators were optimized. Chen et al. (2020a) experimentally and numerically investigated the heat transfer and resistance performance of heat exchangers with symmetric, asymmetric and helical corrugated tubes. The results demonstrated that the heat transfer and resistance performances of each corrugated tube on the shell side were better than those on the tube side. They analyzed the mechanisms of thermodynamics and fluid flow in the enhanced tubes.

3.1.2 Devices, inserts, and coiled tubes

Zheng et al. (2020b) presented a review on single-phase convective heat transfer enhancement based on multi-longitudinal vortices in heat exchanger tubes. Various techniques such as artificial roughness, special-shaped tubes, multiple swirl devices, and longitudinal vortex generators that can construct the flow pattern of multi-longitudinal vortices were summarized and some new perspectives on the existing research gaps, challenging, and future research directions had been provided for the development of enhanced heat transfer techniques by generating multi-longitudinal vortices in heat exchanger tubes in their review. Chu et al. (2020) experimentally investigated the thermo-hydraulic performance of tubes with various twisted tapes in the turbulent transition region and analyzed the heat transfer enhancement performance. Liu and Wang (2020) numerically simulated the vortex motion and decay characteristics in a gas-liquid two-phase swirl flow induced by a short twisted tape and proposed two parameters to quantitatively describe the decay in a two-phase swirl flow. Their results showed that two corotating helical vortices appeared and remained in the swirling flow, and these vortices significantly influenced liquid distribution. Jiang et al. (2020) proposed a new type named symmetrical capsule plate heat exchanger based on the idea of counter-rotating vortices and numerically studied the heat transfer enhancement and the influences of capsule geometries. Counter-rotating vortices generating in the channels promoted the swirl flow and disturbed the boundary layer. Both fluid impingement and the vortices dominated the heat transfer augmentation, which became much stronger under smaller capsule, resulting in higher heat transfer coefficient (HTC). Nakhchi et al. (2020) performed an experimental study on the heat transfer characteristics and friction factors of fluid flow through a heat exchanger tube equipped with double-cut twisted tapes with different cut ratios using water as the working fluid under turbulent flow and concluded that using the double-cut twisted tapes was an effective technique to augment heat transfer in a heat exchanger tube. Park (2020) numerically investigated the effects of the self-sustained oscillating motion of flexible vortex generators on heat transfer. The wall-mounted flexible flag with an inclination angle was used to promote the fluid mixing and increase the heat transfer without much increasing the energy loss. Zhang et al. (2020f) investigated the effects of the configuration of two rectangular winglet vortex generators including parallel type and V-shaped type on turbulent heat transfer enhancement in circular tubes. Mohammadshahi et al. (2020a) conducted experimental and numerical studies on flow characteristics and heat transfer of a double-feedback fluidic oscillator in a channel. A comparison with a free jet revealed that the oscillating jet in a channel is useful in terms of covering a larger area. Mohammadshahi et al. (2020b) studied vortex-induced vibration characteristics and heat transfer mechanism of an oscillating plate attached to a cylinder in a constant-temperature channel. Kumar et al. (2020a) experimentally studied the performance enhancement by perforated twisted tape tube insert with single and double V cuts in a heat exchanger tube under turbulent conditions and compared the performance of a heat exchanger tube fitted with perforated twisted tape insert having single and double V cuts. Ke et al. (2020) enhanced heat transfer by out-of-phase self-vibration through fluid-structure interaction and performed a numerical simulation of fluid-structure interaction effects on vortex dynamics and heat transfer in a rectangular channel with two plates mounted symmetrically across from one another on two channel walls. Heat transfer enhancement technologies through geometry modification in the heat exchanger are grouped into three categories: tube inserts, fins, helical baffles. Promvonge and Skullong (2020) carried out experimental work to evaluate the thermo-hydraulic performance of a heat exchanger tube inserted with two types of V-shaped winglet vortex generators (V-WVGs): 45^{o} V-shaped rectangular- and delta- winglets of different configurations in turbulence region. They found superior heat transfer enhancement (4.58–5.09 times) for both V-WVGs compared to the plain tube. Mohammadi et al. (2020) numerically investigated the thermo-hydraulic performance of a shell and tube heat exchanger (STHX) with porous baffle configurations of varying permeability, porosity and baffle cut. Results showed baffle cut had a substantial impact on the heat transfer performance and low baffle cuts could provide better heat transfer at a penalty of more significant pressure drop. A protracted finned counter flow Heat Exchanger (PFCHE) was designed, analyzed, fabricated and experimented with water-ethanol as the working fluid to reap low-grade waste heat energy exhausted by internal combustion engine. The study obtained a high efficiency (75–90 %) value for PFCHE at full operation, while the heat exchanger efficiency excluding fins was only 20–28.5 % (Ravi et al., 2020).

3.1.3 Additives, nanofluids and nano encapsulated phase change materials

Enhancement of heat transfer using nanofluids has been a hectic topic of research and development since the term "nanofluid" was first used in 1995. Significant progress in this field has been made in the past two decades. Guo (2020) has recently presented a comprehensive review summarizing a variety of the experimentally measured thermal properties of common nanofluids, the enhancement mechanisms discovered or hypothesized, the models used for properties and heat transfer characteristics, and the applications of nanofluids for enhancing heat transfer. Nanofluids, due to their enhanced thermophysical properties, could potentially be used to boost the thermal performance of heat exchangers. Kanthimathi et al. (2020a) conducted experimental investigations on the thermal performance of double pipe heat exchanger using EG-water-based SiC nanofluid under turbulent conditions. Kanthimathi et al. (2020b) experimentally investigated the heat transfer characteristic of single-component Fe_3O_4 and SiC nanoparticles, and the hybrid mixture of Fe_3O_4 and SiC (volume ratio 50:50) in a double pipe heat exchanger with ethylene glycol and water mixture as the working fluid in turbulent flow regime. A maximum heat transfer enhancement of 98.95% was obtained at a flow rate of 6L/min for the 0.08% hybrid nanofluid. Ekiciler et al. (2020) numerically simulated forced convective heat transfer of an Al_2O_3/water nanofluid, having different shapes of nanoparticles including blade, brick, cylindrical, platelet, and spherical, flowing in a 3D equilateral triangular duct. Moosavi et al. (2020) numerically studied turbulent forced convection nanofluid flow with water as base fluid, Al_2O_3 and CuO as nanoparticles over an inclined forward-facing step. CFD simulations were performed for a heated forward-facing step channel with different step lengths and different inclination angles of the step under turbulent conditions. Raja et al. (2020a) conducted an experimental investigation on the enhanced thermal behavior of packed beds integrated with Al_2O_3 nanofluid. Aydın et al. (2020) studied the thermal performance of thermosyphon heat pipe using dolomite/deionized water nanofluid depending on nanoparticle concentration and surfactant type. The effects of using dolomite/deionized water nanofluid on the thermal performance of thermosyphon heat pipe were experimentally investigated. Hajjar et al. (2020) investigated the natural convection of a Nano Encapsulated Phase Change Materials (NEPCM) suspension in a cavity with a hot wall having a time-periodic temperature. Ghalambaz et al. (2020) simulated free convection heat transfer of a suspension of NEPCM in an inclined porous cavity. The results also showed that the presence of the NEPCM particles generally led to heat transfer improvement. Mehryan et al. (2020) simulated the free convective flow of a NEPCM suspension in an eccentric annulus and found a 5% volume fraction represents the optimal value for heat transfer enhancement. Ho et al. (2020a) conducted an experimental study on forced convection heat transfer of NEPCM suspension in a mini-channel heat sink and observed the enhancement of heat transfer was particularly notable at low Reynolds numbers.

3.2. Active Techniques

3.2.1 Mechanical aids, surface or fluid vibration

Wang et al. (2020b) presented a review on the recent development of corona wind and its application in heat transfer enhancement and discussed the formation process of corona wind and the mechanism of local heat dissipation enhancement from the perspectives of physics, electricity and thermodynamics. Setareh et al. (2020) conducted experimental and numerical studies of heat transfer enhancement of water fluid flow in an annulus under ultrasonic waves. The cross-flow generated by circulations due to acoustic streaming was responsible for heat transfer augmentation. Zhang et al. (2020a) numerically investigated ultrasound-assisted enhancement of heat transfer in staggered pipes and analyzed the influence of various operational parameters on heat transfer enhancement. Zhang et al. (2020b) analyzed and simulated the enhanced mechanism of heat transfer associated with ultrasonic vibration. They also conducted case studies on applying the ultrasonic technique. Legay et al. (2020) analyzed several qualitative and quantitative methods to evaluate the heat transfer enhancement performances of an ultrasonically assisted double tube heat exchanger. Hashim et al. (2020) conducted an experimental study of water jet impingement cooling on a heated horizontal SS-304 plate and analyzed the effects of various parameters on the cooling heat transfer enhancement.

3.2.2 Electro-magnetic fields

Bezaatpour and Goharkhah (2020) numerically investigated an innovative method based on applying an external magnetic field to generate a swirling flow in the magnetic working fluid to improve the convective heat transfer in heat exchangers and also reduce the pressure drop penalty compared to the other conventional enhancement techniques. Bezaatpour and Rostamzadeh (2020) numerically investigated the effect of a uniform external magnetic field with Fe_3O_4/water nanofluid for heat transfer enhancement of a fin-and-tube compact heat exchanger and validated the simulations with experimental data. Krakov and Nikiforov (2020) investigated heat transfer enhancement behavior of magnetic fluid or gaseous oxygen thermomagnetic convection in the annulus between horizontal cylinders under the influence of gravitational and magnetic forces. The influence of the shape of the inner cylinder and the magnitude of the magnetic field gradient on the heat transfer were studied. Maroofiazar and Eshkalak (2020) conducted numerical investigations of mixed convection of power-law non-Newtonian ferrofluids in a concentric annulus under the influence of a nonuniform magnetic field and considered the effects of ferrohydrodynamics (FHD) and magnetohydrodynamics (MHD) simultaneously. Tang et al. (2020a) experimentally investigated the effects of applied non-uniform electric field generated by pin electrodes on evaporation heat transfer enhancement in a vertical rectangular microgrooves heat sink. The electric field can promote the capillary wetting length, decrease the wall temperature of microgrooves and enhance the heat transfer performances effectively. Jafari and Goharkhah (2020) numerically investigated the effect of a 3D magnetic field generated by four electromagnets on the forced convective heat transfer of Fe_3O_4 /Water ferrofluid in a parallel plate channel. Dixit and Pattamatta (2020) conducted an experimental study on the effect of external uniform magnetic-field on natural convection heat transfer in magnetite and iron nano-dispersion in a differentially heated cubical cavity. Samsam-Khayani et al. (2020) numerically examined the effects of a constant nonuniform magnetic field on the laminar forced convective heat transfer of a hybrid nanofluid flowing through a heated annular tube and containing Fe_3O_4 nanoparticles and carbon nanotubes (CNTs) in laminar flow. Giwa et al. (2020) investigated the effects of uniform magnetic induction on free convection heat transfer performance of aqueous Fe_2O_3-Al_2O_3 (75:25) nanofluids in a rectangular cavity under magnetic induction. Alami et al. (2020) carried out experiments to enhance heat transfer in agitated vessels by alternating magnetic field stirring of aqueous Fe-Cu nanofluid. Plotnikov and Leal-Quiros (2020) analyzed the effect of pulsed electrical discharges generated in liquid-phase ethanol in a pin-to-plate reactor experimentally and computationally.

3.3. Compound Techniques

Many studies used a combination of passive and active enhancement techniques. Kumar et al. (2020c) conducted an experimental study of Zinc Oxide/water/ethylene glycol-based nanofluid in a square duct roughened with inclined ribs for various sets of geometric and flow parameters. Allauddin et al. (2020) numerically investigated heat transfer enhancement caused by impinging jets of Al_2O_3-water nanofluid on a micro-pin fin roughened surface under crossflow and turbulent conditions. Yang et al. (2020a) performed experimental investigations on the combined effect of nanofluid and ultrasonic field on ammonia bubble absorption and considered the enhancement effect of nanofluid and ultrasonic fields separately and simultaneously on ammonia bubble absorption in the absorber for improving the efficiency of the absorption refrigeration system. Wang et al. (2020a) executed experiments to study natural convection heat transfer characteristics of TiO_2–H_2O nanofluids in a cavity filled with different pore density copper foam. Beigzadeh and Eiamsaard (2020) conducted modeling of a heat transfer enhancement system including CuO/water nanofluid in a corrugated tube equipped with twisted tape using two well-known artificial neural network techniques and ran genetic algorithm multiobjective optimization of the thermal system with three heat transfer enhancement characteristics. Fathian et al. (2020) studied the effect of adding single-walled and multi-walled carbon nanotubes to distilled water upon the heat transfer characteristics of the flow in helical annuli which was formed by twisting a straight double-tube heat exchanger. Khoshvaght-Aliabadi and Feizabadi (2020) proposed a new passive compound heat transfer enhancement technique through a corrugated wall structure to enhance the overall hydrothermal performance of helical channel with square cross-section in the laminar flow regime. Kurnia et al. (2020) numerically investigated flow behavior and the corresponding heat transfer in helical tube with twisted tape insert subjected to constant wall temperature in the laminar convection heat transfer. Ali et al. (2020) conducted an experimental study of natural heat transfer enhancement in a rectangular finned surface by combining the active and inactive methods of heat transfer enhancement and examined the effect of electrohydrodynamics (EHD) on natural heat transfer on a rectangular surface with vertical fin. Sarlak et al. (2020) numerically inspected MHD mixed convection of water/CuO nanofluid in a square enclosure with vortex generators in different arrangements. Zheng et al. (2020a) investigated heat transfer performance and flow characteristics of various nanofluids (with the addition of nanoparticles of Al_2O_3-30nm, SiC-40nm, CuO-30nm and Fe_3O_4-25nm at mass fraction 0.05-1.0 wt.%) in a corrugated plate heat exchanger used in solar energy systems and concluded that 1.0 wt.% Fe_3O_4-water nanofluid possessed the best thermal performance, exhibiting a 21.9% increase of convective heat transfer coefficient and 10.1% increase of pressure drop compared to deionized water. The graphene nanofluid was used in the heat exchanger's tube side to enhance its heat transfer performance, which showed a maximum increase in the heat transfer coefficient of 29% at mass fraction 0.2 wt.% (Fares et al., 2020). Fathian et al. (2020) investigated the effect of adding single-walled and multi-walled carbon nanotubes to distilled water upon the heat transfer characteristics of the flow in helical heat exchangers with varying annulus curvature ratios.

3.4 System Optimization

Kumar et al. (2020d) proposed multi-objective wale optimization (MOWO) algorithm as an optimization technique to improve the heat transfer and reduce the pressure drop in the plate heat exchanger by varying the horizontal, vertical port distance, plate facing and plate thickness. Beigzadeh and Eiamsa-ard (2020) modeled a heat exchanger including CuO/water nanofluid in a corrugated tube equipped with twisted tape through two well-known artificial neural network techniques. Sadeghianjahromi et al. (2020) numerically investigated in detail the effects of louver angle, fin pitch, transversal tube pitch, and longitudinal tube pitch on Colburn and friction factors in louver fin-and-tube heat exchangers and found the optimum louver angle was around 20° for maximizing Colburn factor and minimizing friction factor. Klemeš et al. (2020) reviewed heat transfer enhancement, intensification and optimization of heat exchanger network retrofit problem considering practical operational issues.

4. Radiation

In this section, the studies on radiation heat transfer enhancement are reviewed with foci on near-field radiation and solar energy.

4.1 Near-field Radiation

With miniaturization in electronic-mechanical devices, active tuning of near-field radiation heat transfer (NFRHT) has attracted great attentions of research for both fundamental and applicative reasons. Rapid progress has been achieved in NFRHT in recent years. Zhang (2020) laid out an excellent overview on micro/nanoscale thermal radiation. Controlling and enhancing NFRHT is critical for many applications such as photonic thermal rectification and near-field thermophotovoltaics. Thompson et al. (2020) reported that the radiative heat transfer between two coplanar SiN membranes in the far-field could be modulated by factors as large as five by bringing a third planar object into close proximity of the membranes. The modulation of NFRHT between twisted nanoparticle gratings was studied by Luo et al. (2020b). Characteristic oscillations of the thermal conductance were observed and fully due to finite-size effect which is beyond the effective medium approximation. He et al. (2020) reported that NFRHT could be tuned by adjusting the strength of magnetic field and the graphene grating effect simultaneously. The combined effect provided a tunable way to realize energy modulation or multi-frequency thermal communications. Wu and Liu (2020) studied the NFRHT between graphene covered biaxial hyperbolic crystal α-MoO_3 and showed that the coupling between plasmons in graphene and phonon polaritons in α-MoO_3 could greatly enhance the total heat flux. By modulating the near-field radiative heat transfer among graphene/SiC core-shell nanoparticles, Song et al. (2020c) achieved thermal routing to address the directional heat flow manipulation in a particular many-body setup. It was found that graphene remarkably modified the surface resonance and introduced additional modes.

Bhatt et al. (2020) integrated near-field thermo-photovoltaics for heat recycling and revealed over an order of magnitude enhancement of power generation by actively tuning the gap between a hot-emitter and the cold photodetector with negligible tuning power. Song et al. (2020b) presented a theoretical demonstration of dynamically tunable NFRHT between two multilayer hyperbolic metamaterials using an external magnetic field and found the hybridization of intrinsic and magnetization-induced hyperbolic modes could significantly enhance the radiative heat transfer. Chen et al. (2020c) implemented topology optimization to inversely design a metallic nanoparticle dimer to optimize the near-field enhancement factor in its sub-10 nm gap. Wang et al. (2020f) demonstrated the effect of mechanical strain on the NFRHT between two separate black phosphorous sheets and achieved 73% increase in the near-field HTC by applying 6% zigzag uniaxial or 4% biaxial strain.

Tang et al. (2020b) measured NFRHT between millimeter-size surfaces made of 6H-SiC and doped Si, respectively, supporting surface phonon-polaritons (SPhPs) and surface plasmon-polaritons (SPPs) in the infrared, separated by a 150 nm thick vacuum gap spacing maintained via SiO_2 nanopillars. They found that the near-field enhancement for the SiC-Si sample exhibited a more pronounced monochromatic behavior, with a resonant flux that is around 5 times larger than the resonant flux for the Si–Si sample. Papadakis et al. (2020) proposed a versatile design strategy for broadening the emission spectrum via stacking multiple plasmonic thin film layers in surface polariton mediated near-field thermophotovoltaics to improve power density and efficiency. Salihoglu et al. (2020) reported radiation enhancement in the near-field regime between two bulk and rigid parallel plates, in which embedded temperature sensors to allow and maintain near-zero separation were employed. Their finding matched the theoretical prediction of an 18,000 times enhancement in radiation between two parallel quartz plates with separation down to 7 nm.

4.2 Solar Energy

Solar energy is a vast, inexhaustible, and clean resource, which can be used for heating and lighting homes, generating electricity, seawater desalination, and a variety of other commercial and industrial uses. A lot of research has been focusing on improving the efficiency of solar energy harvest devices and systems. Concentrated solar power (CSP) plant is a promising way to achieve low-cost commercial power generation in the near future. Molten salts are known for their advantages, such as being cheap, abundant in supply and high-temperature compatibility, permitting them for potential application as sensible storage media and heat transfer fluid for CSP plants. Aljaerani et al. (2020) reviewed the enhancement of CSP plant efficiency via use of nano-enhanced molten salts. Sahin et al. (2020) had done an extensive review on various recent studies that illustrated the use of nanofluids in different types of solar collectors for improvement of their performance, among which carbon nanotubes resulted in larger enhancement when compared to rest. Senthil (2020) experimentally investigated the charging of phase-change material (PCM) in a concentrated solar receiver and found that the PCM-filled solar receiver possessed the ability to retain the temperature of the receiver, about three times more than the non-PCM receiver due to the constant temperature melting of PCM. Zayed et al. (2020) simultaneously maximized the output power and total efficiency of the dish/Stirling CSP system using multi-objective particle swarm optimization considering nine decision variables, namely, the interception factor, mirror reflectance of the concentrator, receiver absorbance, receiver transmittance, receiver emissivity, tilt angle of the receiver, the direct solar intensity, the speed of wind, and the temperature of ambient. Wang et al. (2020d) proposed blended nanofluids based on Ag triangular nanosheets and Au nanorods to enhance photothermal conversion and obtained a high efficiency of 76.9% experimentally with a very low volume concentration (0.0001%). In order to enhance overall energy harvesting from the solar irradiation, Mohammadnia et al. (2020) proposed a novel hybrid energy harvesting system based on separation of the solar irradiation and comprising a solar concentrator, concentrated photovoltaic, beam splitter, cavity, Stirling engine and solar thermoelectric generators.

Cai et al. (2020) examined the performance of Ni water-based nanofluid in a glass louver for illumination and energy harvesting dual-purpose and found that the dilute 0.00004 vol% Ni-water nanofluid with particle diameter of 80 nm could absorb more solar energy and provided required daylighting. Nan et al. (2020) numerically investigated the solar energy harvest efficiency of a proposed water-filled prismatic glass louver that could be deployed in buildings to improve natural lighting as well as to harvest solar energy. Zhou et al. (2020e) developed high thermal energy storage thermo-responsive smart window by trapping the hydrogel-derived liquid within glasses. At lower temperatures, the window was transparent to let in the solar transmission; when heated, the window blocked sunlight automatically to cut off solar gain. A Novel 3D evaporator composed of a base evaporation surface and vertical fins located above the base surface was designed to deliver an extremely high-efficient solar-steam generation system, holding promising applications for desalination and wastewater treatment (Wang et al., 2020e). Sharshir et al. (2020)

investigated a new combination of v-corrugated basin with wick and CuO nanofluids for performance enhancement of pyramid solar distiller. The results showed that the thermal efficiency with the combination was 60.5% compared to only 34% without.

Al-Gebory and Menguc (2020) provided an excellent review on the optical and radiative properties of nanoparticle suspensions. As the review emphasized, understanding interactions of electromagnetic radiation with the nanoparticles is of critical importance to develop a wide range of applications as well as to optimize systems and components. The authors extensively evaluated a wide range of effects and concerns on particle long-term stability, agglomeration, and sedimentation under different conditions. They found a close relationship between particle agglomeration and the optical and radiative properties of nanofluids. The effects of particle types, sizes on individual, hybrid, and agglomerated nanoparticle suspensions, as well as the effect of pH values, were discussed. Some simple approaches to manipulate particle agglomeration, and consequently, the optical/radiative properties of nanofluids were introduced.

Solar energy has been utilized for seawater desalination either by producing the thermal energy required to drive the phase-change processes or by producing electricity required to drive the membrane processes. Passive vapor generation with interfacial solar heat localization could achieve high-efficiency low-cost seawater desalination. Xu et al. (2020c) realized 385% solar-to-vapor conversion efficiency and a production rate of 5.78 $Lm^{-2}h^{-1}$ in a multistage solar still. Essa et al. (2020) introduced a new mechanism of distillation via modifying a solar still with a rotational disc. It was found that the distillate of the rotating corrugated disc's distiller with wick was improved by 124%. Experiments to examine the influences of nanofluid and high altitude (high UV light) for water desalination and solar water disinfection were executed by Parsa et al.

(2020). Results showed that from energetic point of view, utilizing nanofluid has great impact on the systems while from exergetic viewpoint the altitude has the greatest impact on the systems. The produced water was healthier because of using both Ag nanoparticle and solar disinfection methods.

5. Boiling and Condensation Heat Transfer

Boiling and condensation heat transfer is widely applied in various engineering processes and can be enhanced using various techniques. New emerging research on boiling and condensation heat transfer enhancement using micro- and nano-technology has been developed, e.g., micro-and nano-structured surfaces, additives of nanoparticles and environmentally friend surfactants, microchannels and so on. In the meantime, traditional enhancement techniques such as microfin tubes, inserts, applying electric field and so on are continuously investigated for advanced mechanistic and theoretical knowledge and engineering applications.

5.1 Boiling Heat Transfer

A large number of studies on enhancement of both pool boiling and flow boiling have been conducted to understand the phenomena and mechanisms and apply to engineering practice.

Gouda et al. (2020) conducted experimental investigation of pool boiling on a smooth copper surface with aqueous biosurfactant (Rhamnolipid) solutions at different concentrations. The Rhamnolipids solution showed better heat transfer performance and higher critical heat flux (CHF) value compared to sodium dodecyl sulfate surfactant. Ispir and Onbasioglu (2020) experimentally investigated tunnel width, pore, and height size effects on boiling heat transfer and the performance of surfaces in different ranges of heat fluxes and observed the behavior of nucleation of vapor bubbles. Mehdi and Kim (2020) investigated the role of pore geometry (pore diameter and pore pitch) on pore/subtunnel surfaces using the refrigerant R-123, and the results were compared with those of R-134a. Kumar et al. (2020b) experimentally investigated confined pool boiling with aqueous surfactant solutions under various subcoolings, heater orientations, and confinement gaps. A maximum of 120% increase in HTC and 280% increase in CHF with surfactant was observed in comparison to the baseline case of pure water.

Surface wettability engineering is an effective tool for enhancing heat transfer in boiling. Sarode et al. (2020) experimentally investigated and compared the individual effects of confinement and orientation (horizontal and vertical) on the HTC obtained during boiling on macroscale-patterned wettability surfaces with the baseline case of a homogeneous wettability bare surface. The baseline hydrophilic substrate was modified using macroscale hydrophobic dots with a sufficiently large pitch to avoid lateral bubble coalescence on the modified patterned wettability surfaces. The modified surface demonstrated a better heat transfer performance than the bare surface. Sajjad et al. (2020) reported a substantial enhancement mechanism by optimizing the morphological parameters of sintered Cu/Ni alloy surfaces. An increase in the nucleation site densities of sintered surfaces by controlling the average surface roughness, porosity, particle diameter, and coating thickness yielded substantial augmentation in pool boiling of a highly wetting liquid. Shen et al. (2020) claimed that wettability-patterned (so-called biphilic) surfaces were nearly free of severe degradation of heat transfer performance in subatmospheric boiling, attributed to the strong pinning of the three-phase contact line (TPCL) at the border between the hydrophobic and hydrophilic surfaces.

Nithyanandam and Kumar (2020) conducted experimental investigations of nucleate boiling heat transfer on the copper substrates coated with SiO_2 and copper hybrid thin film using the radio frequency sputtering method. The results showed that the boiling heat transfer and critical heat flux are enhanced. Zakset et al. (2020) conducted experiments to compare nucleate pool boiling performance on plain and laser-textured stainless-steel foils. Significant decreases in the HTC and increases in the bubble activation temperature were discovered for the plain surfaces in comparison with the laser-textured surfaces. A 280% enhancement in HTC on a textured heating surface was recorded using pure water; while a 268% enhancement was achieved on a heating surface using pure ethanol. It was concluded that laser texturing can significantly improve boiling performance when the intervals of the laser-textured patterns are close to the capillary lengths of the fluids.

Nanoscale boiling heat transfer can reach extremely high heat flux. Due to its complex multiphase system, the mechanism of nanoscale boiling heat transfer awaits to be studied and revealed. Moze et al. (2020) reported that nanoscale superhydrophobic coating on a laser-engineered microcavity surface could enhance its HTC by over 500%. The enhancement of boiling heat transfer confirms that the Wenzel wetting regime is possible during boiling on superhydrophobic surfaces. Liang et al. (2020) studied nucleate boiling on micro-pit surfaces. They found that micro-pit surface could reduce boiling incipience superheat and improve nucleate boiling and its CHF. They also reported an optimum pit-to-pit spacing for maximum boiling enhancement, which was identical to capillary length. Hu et al. (2020a) reported that roughness enhances thin-film evaporation when the effect of disjoining pressure is more pronounced and it inhibits thick-film evaporation when the effect of flow permeability is more pronounced.

Based on Newton's equations of motion, MD can simulate a relatively larger system compared to the first principles method. Hence, MD is used as an alternative way to explore nanoscale boiling heat transfer. Xie et al. (2020) employed the lattice Boltzmann method (LBM) to simulate the effect of surface orientation, wettability, geometric size, and subcooling of the downward-facing lower head on the CHF enhancement. The results showed that for the downward-facing surface, the CHF increased with increasing surface orientation while a vertical surface gave a slightly lower CHF compared to a near-vertical surface. Wu et al. (2020a) reported that a microfluidic layer formed only on hydrophilic surface was conducive to CHF improvement and weaker attraction of water molecules upon hydrophobic surface was conducive to boiling HTC improvement. Yang et al. (2020b) reported that the thermal conductance of graphene oxide rose under the increasing degree of oxidation and monatomic vacancy. Cao et al. (2020) developed a mathematical optimization method of the grooved nanostructured surface design. They found that the heat transfer performance exhibited a positive correlation with the defined sectional area of the grooved nanostructured surface. Liu et al. (2020a) studied boiling heat transfer on nanostructured surfaces and found that the bubble nucleation time was advanced, and the heat transfer efficiency was enhanced compared to the smooth surface. By increasing the solid-liquid contact area, the interaction energy per unit area could increase, which led to the decrease of interfacial thermal resistance.

Axial microfins are promising means for enhancing evaporation of refrigerants in tubes. Evaporation heat transfer and pressure drop tests were carried out on four tubes−smooth, helical microfin, axial microfin using R-410A (Han et al., 2020). Experiments of enhancement of flow boiling with R407C were conducted inside tubes with discrete internal structures and the heat transfer characteristics were compared with a micro-fin tube (Darshan et al., 2020). It was observed that the heat transfer of R407C inside the enhanced tubes was better than that of the microfin tube. Kong et. al. (2020) realized simultaneous visualization and measurement to investigate the onset of nucleate boiling (ONB) phenomenon of deionized water in circular, diamond, and oval micro pin fin heat sinks. The results showed that the heat flux and wall superheat needed for the ONB increased as the mass flux and inlet subcooling increased. Moreover, the heat flux required for the ONB in the diamond and oval micro pin fin heat sinks was higher than that in the circular one. A microchannel with triangular cavities and rectangular fins was fabricated for flow boiling improvement and flow boiling experiments were carried out using pure acetone at various conditions. Li et al. (2020e) investigated the flow boiling characteristics of the microchannels with triangular cavities and rectangular fins. The results indicated that the microchannels showed significantly enhanced heat transfer, reduced ONB, and delayed CHF as compared to conventional microchannels.

5.2 Condensation Heat Transfer

Tsuruta and Tokunaga (2020) introduced a wettability gradient by gradually changing the pattern widths of the hydrophobic and hydrophilic surfaces. Their experimental results show that the flooding was suppressed, and the heat transfer coefficient was enhanced by three times compared with the results of the microstructured condensing surface with a straight pattern. Kim (2020) experimentally investigated condensation heat transfer and pressure drop on four tubes‒smooth, helical microfin and axial microfin using R-410A. Çiftçi and Sözen (2020) conducted experiments of boiling and condensation with dichloromethane and hexagonal boron nitride/dichloromethane nanofluid solutions to specify nanoparticles' effect on thermal performance. The results showed that enhancement of boiling and condensation heat transfer had been achieved. Wang et al. (2020c) experimentally studied the condensation heat transfer characteristics of R290 (propane) in a horizontal smooth copper tube and a microfinned copper tube. The results show enhancement heat transfer characteristics in the microfinned tube. Bai et al. (2020) explored condensation heat transfer inside small diverging channels. and found the diverging channel enhanced local condensation heat transfer even with very small diverging angles. Li and Du (2020) investigated the influence of noncondensable gases on phase change in confined nanoscale space by using molecular dynamics simulation. The enhancement of heat transfer could be realized and controlled through the regulation of the noncondensable gases in the working fluid. Diani et al. (2020) performed a direct comparison of condensation heat transfer of R513A in a smooth tube and a microfin tube. The results showed that the microfin tube leads to a real heat transfer augmentation.

Dropwise condensation of steam on hydrophobic surfaces has a 10 times higher HTC compared to filmwise condensation (Chang et al., 2020). Low surface energy hydrophobic coatings such as polymers are usually employed to promote dropwise condensation in applications such as power generation, water treatment, and thermal management of electronics and high-performance equipment. Polymer coating must be thin (< 1μm) because of the low thermal conductivity with polymer materials; and thus, it tends to degrade quickly. To solve this issue, Chang et al. (2020) developed metal-polymer structured surfaces to enhance the coating effective thermal conductivity and surface energy. Wilke et al. (2020) achieved dropwise condensation heat transfer enhancement for more than 200 days without significant degradation by infusing a hydrophobic polymer, Teflon AF (amorphous fluoropolymer), into a porous nanostructured surface. They demonstrated over 700% enhancement in the condensation of steam compared to an uncoated surface. Lee et al. (2020a) experimentally investigated the droplet behavior on a superhydrophobic plate to understand the droplet detachment and attachment in accordance with the surface and droplet temperatures. The results were represented as a "droplet-behavior map", which clearly depicts boundaries dividing the detachment and attachment regions. Zhang et al. (2020g) investigated steam condensation heat transfer on a honeycomb-like microporous superhydrophobic surface. The results showed that stable coalescence-induced droplet jumped with high heat flux with non-condensable gas concentrations up to 28%.

5.3 Two-Phase Heat Exchangers

Two-phase heat exchangers suitable for high heat load applications have attracted growing research interest. Liu and Wang (2020) numerically studied the flow and thermal characteristics of the gas-liquid two-phase flow induced by a short twisted tape for heat exchanger applications and elucidated the vortex motion and decay characteristics. A mini-channel two-phase heat exchanger with a sudden expansion structure was proposed to enable its high operational efficiency (Liu et al., 2020b). Chien et al. (2020) compared the falling film evaporation in serrated fin tubes made by electrical discharge machining and smooth tube, which showed serrated fin tube yielded enhancement ratios of up to 10.18 and 6.02 for falling film evaporation of R134a at 10°C and 20 °C, respectively. Evaporation heat transfer and pressure drop tests were performed on four small diameter (7.0 mm) tubes with smooth, helical microfin, axial microfin, and spoke for the mass flux from 50-250 $kgm^{-2}s^{-1}$ using R-410A at heat flux of 3.0 kWm^{-2}. Axial microfin tube was found to yield the best heat conductance enhancement for high mass flux (> 150 $kgm^{-2}s^{-1}$) and the spoke tube provided the best enhancement at lower mass fluxes (Han et al., 2020). Enhancement of flow boiling could be realized by developing an internally microdimpled (IMD) tube and a tube with internal bidirectional tunnel structure (BTS). It was observed that the heat transfer coefficient of R407C inside both the IMD and BTS tubes was better than that of the MF tube (Darshan et al., 2020).

6. Thermal Energy and Energy Storage

Energy storage becomes a more and more important topic in the past year not only because it can reduce the energy gap between supply and demand by the development of modern technology industrials, but also because it can enhance the energy conservation performance to provide a reliable insurance when there is a power outage of grid due to natural or artificial disaster. Not long ago, US Texas's massive failure of electricity grid contributed to several deaths of people and loss of billions of dollars in property damage as the lack of a stable energy storage system which could provide alternative energy supply when the normal grid system was down. President Biden planned to take the executive action with the investment of 2 trillion dollars on the development of green energy storage due to increasing energy demand and climate crisis. Energy storage, especially clean and renewable energy storage, will continue to be a critical challenge and growing interest area for researchers to overcome in the future.

Thermal energy storage (TES) is one of the most common and reliable forms of energy storage for renewable energy. Heat transfer enhancement technologies for TES, mainly phase-change materials (PCMs) and nanofluids (NFs), were used to enhance the effectiveness of TES (Hussam et al., 2020; Guo et al., 2020).

6.1 Phase Change Material (PCM)

PCMs are investigated as a suitable solution for thermal energy storage enhancement, as PCMs have high density and stability of thermal energy stored at nearly constant temperature during the phase change process. However, PCMs also suffer from their low thermal conductivity in the latent heat thermal energy storage (LHTES) system. Different methods of thermal conductivity enhancement on PCMs were reviewed by Wu et al. (2020c). Methods of thermal conductivity enhancement on PCMs are mainly grouped into two categories: PCMs encapsulation and nanomaterial additives.

6.1.1 Encapsulated Phase Change Material (EPCM)

Free convection heat transfer of a suspension of nano–encapsulated phase change materials (NEPCMs) of nonadecane within polyurethane shells dispersed into the water in an inclined porous cavity was numerically analyzed, achieving about 13% heat transfer improvement for the presence of the NEPCM particles at the inclination angle of 42° at solid-liquid fraction of 0.5, and up to a possible maximum of about 28% enhancement in the heat transfer at the inclination angle of 82° (Ghalambaz et al., 2020). NEPCMs consisting of Sn/SnO_x nanoparticles capsulated with SiO_2 and Al_2O_3 synthesized by Atomic Layer Deposition were experimentally demonstrated, and an overall 10.5% enhanced thermal energy storage capacity of the nanofluids when the NEPCMs encapsulated with Al_2O_3 nanoparticles with respect to the solar salt was found (Navarrete et al., 2020). Shi et al. (2020) numerically studied a NEPCM filled cylindrical shell-and-multi tube thermal energy storage system (TESS) in the presence of magnetic field (MF) generated by quadrupole magnets and found that by applying the MF, both the charging and release processes of the TESS were shortened. Bhagat et al. (2020) numerically developed a latent heat thermal storage system packed with spherical encapsulated PCMs based on the momentum equation and nonequilibrium two-temperature energy equations for PCM and HTF and the enthalpy–porosity technique for the isothermal phase change of the PCM, and evaluated that a smaller inner encapsulation diameter and lower porosity resulted in more entropy during the discharging process and the encapsulation shell thickness insignificantly affected the entropy generation and the first-law efficiency.

6.1.2 Nano Particle (NP) Additives

A tubular solar still with nano particle of graphene oxide limited to 0.3% concentration in PCM (NPCM) was experimentally studied, resulting the thermal conductivity of NPCM be improved by 52% as compared to PCM without nanoparticle as additive material (Kabeel et al., 2020). Zhou et al. (2020c) both experimentally and numerically demonstrated the promotion of thermal conductivity to as high as 10~50 $Wm^{-1}K^{-1}$ of composite PCM of aqueous ethylene glycol (EG) consisting of nanoparticles of multiwalled carbon nanotubes (MWCNTs), compared with pure PCM had a poor thermal conductivity as low as 0.2~0.5 $Wm^{-1}K^{-1}$, by forming effective conduction paths composed of backbones in the composite PCM. The influence of Ag nanoparticles on the enhancement of thermal energy storage of paraffin wax as PCM was studied experimentally, showing that the average temperature rise or fall had been reduced to 11% and 29.5% with 0.05% and 0.1% concentrations of Ag nanoparticles, respectively (Pradeep et al., 2020). Jourabian et al. (2020a) inserted mono Cu and hybrid Ag/MgO nanoparticles into a horizontal 90° inclination H-shaped capsule with adiabatic curved sidewalls made of ice, and found melting time was diminished 13.6 and 24.5%, respectively, compared to pure PCM melting, when the volume fraction of hybrid nanoparticles was increased from 0.0 to 0.01 and 0.02, respectively, along with mono Cu nanoparticles gave a better thermal performance in contrast to Ag–MgO hybrid nanoparticles. Raja et al. (2020b) investigated a square-geometry analytical model of two-phase system which was comprised of solid and liquid with nanoparticles as a third phase dispersed in the liquid phase, and found the effective thermal conductivity (ETC) of 33% above the Calmidi results and about 51% over the Dietrich model by optimization of the primary, secondary, and tertiary parameters.

6.1.3 Other Methods

Besides PCMs encapsulation and nanomaterial additives, Xu et al. (2020b) experimentally investigated the effects of copper foam and ultrasonic waves on the performance of a gallium heat regenerator, and concluded that the total melting time for the gallium with added copper foam and ultrasonic waves was reduced by 10% and 17%, respectively. Li et al. (2020a) synthesized diatomite-based composites by absorbing lauric acid-stearic acid (LA-SA) into the diatomite-based support under melting impregnation process, and found that the LA-SA/D (raw diatomite), LA-SA/D_m (diatomite after microwave-acid treatment), and LA-SA/D_m/EG (expanded graphite (EG) was introduced as a support matrix together with D_m at a weight ratio of 1:10 of EG to D_m) composites melt at 31.16 , 31.16 , and 31.17 °C, with the latent heat at melting of 59.60 J g^{-1} for LA-SA/D, 76.16 J g^{-1} for LA-SA/D_m, and 117.30 J g^{-1} for LA-SA/D_m/EG, and the different loading capability of D and D_m for LA-SA were 70.36% and 107.04%, indicating that the diatomite processed the better loading capability after microwave-acid treatment. Zhang et al. (2020d) prepared novel composite PCMs with superior thermal conductivity, latent heat, and light-thermal conversion, using TiO_2-TiC-C loaded expanded vermiculite (EVT) as a supporting matrix and lauric-myristic-stearic eutectic mixture (LA-MA-SA) as a PCM. The EVT was further acidized (EVTa) to enhance its PCM absorbability. It was found that the thermal conductivity of LA-MA-SA/EVTa (0.676 W $m^{-1}K^{-1}$) and LA-MA-SA/EVT (0.694 $Wm^{-1}K^{-1}$) were 51.2% and 55.3% higher than that of LA-MA-SA/EV (expanded vermiculite (EV)), and the melting latent heats of LA-MA-SA/EVTa and LA-MA-SA/EVT were 115.7 and 105.8 Jg^{-1}, respectively, which were 45.2% and 32.7% higher than that of LA-MA-SA/EV. Jourabian et al. (2020b) examined the constrained ice melting with natural convection inside a horizontal enclosure with cross section of major circle sector by two-dimensional temperature-based lattice Boltzmann method (TLBM) in single-phase framework, and concluded 45º inclination angle of the horizontal container in the clockwise direction engendered complete melting of pure PCM, increments of the average temperature of pure PCM, and intensity of convective currents inside pure molten PCM. Guo et al. (2020) both experimentally and numerically studied the effect of inclination angle of the partition plate between two PCMs in a two-stage series cascade heat storage device and concluded one should make the partition plate tilts to the direction opposite to the one in which the heat flux is input to enhance its performance of the heat storage.

6.1.4 PCM Applications

In the field of PCM applications, a compact TES device containing a PCM used serrated fins in the air side and perforated straight fins in the PCM side for transport air-conditioning applications were designed and experimentally investigated for smoothing cooling load of transport air conditioning systems, achieving a fast response with the hot air flow cooled down to the desired temperature range of 16–20 °C in seconds and the discharging energy efficiency reached up to 99.8%, with the discharging depth above 97.0% (Nie et al., 2020). A PCM-based solar thermoelectric energy-harvesting device essential to wireless monitoring systems in alpine regions was numerically proposed to generate an increase of 39.57% and 73.3% in the average output power on January 15, 2016 and July 15, 2016, respectively, in Qinghai, China, compared with the non-PCM unit (Cui et al., 2020).

6.2 Nanofluids

Use of nanofluids is also a passive way of thermal energy storage enhancement. Compared with the pure base fluids, adding nano particles into the base fluid induce a significant rise in thermal conductivity and heat transfer coefficient, leading to the enhancement of thermal energy storage. Guo et al. (2020) summarized a variety of the experimentally measured thermal properties of common nanofluids, the enhancement mechanisms discovered or hypothesized, the models used for properties and heat transfer characteristics, and the applications of nanofluids for enhancing heat transfer. Allauddin et al. (2020) numerically studied a micro-pin fin roughened target plate with multiple impinging jets of Al_2O_3–water nanofluid, and observed about 72% improvement in the heat transfer coefficient of the nanofluid at volumetric concentration of 3%. Çiftçi et al. (2020) experimentally investigated hexagonal boron nitride material mixed with dichloromethane (h-BN/DCM) nanofluid pool in varying heater powers ranging from 50 to 350 W to study the boiling and condensation heat transfer, and found the increment rates in the heat transfer coefficient for saturation, superheat, and condensation conditions as 27.6%, 10.4%, and 17.65%, respectively, at an optimum nanoparticle concentration of 1.0%.

6.3 Thermal Battery

In addition, thermal battery energy storage was also studied. Moller et al. (2020) overcame the capacity degradation of pure $CaCO_3$ as a function of calcination/carbonation cycling by the addition of either ZrO_2 (40 wt%) or Al_2O_3 (20 wt%), which resulted in 500 energy storage cycles at over 80% capacity, and found the system had a rapid response time with 60% of the full energy capacity stored or released within 1 hour, while the operating temperature of 900 °C. Ding et al. (2020) investigated the performance of an efficient and compact thermal battery based on a novel double-effect absorption thermal energy storage cycle, and found energy storage efficiency increased by up to 61.6% for cooling and 61.8% for heating for charging temperatures above 160 °C. Li et al. (2020d) experimentally developed and investigated the salt-hydrate $LiOH \cdot H_2O$ with 8 wt% expanded graphite (EG) doping based thermochemical materials (TCMs) used for low-temperature TES, and found the thermal efficiency for heat charging was 83.6%. Huang et al. (2020a) carried out three-dimensional computational fluid dynamics simulations on gas–solid fix-bed reactor for the $Ca(OH)_2/CaO$ thermochemical energy storage system, and concluded that increasing heat conductivity and reaction rate of the bed could enhance the reaction performances dramatically for both dehydration and hydration, the decrease of the wall temperature had an obvious positive influence on dehydration reaction and the decrease of the porosity had an apparent positive influence on hydration reaction, and the reaction rate almost had no effect on the entropy productions of reaction and mass transfer during the dehydration reaction while the reaction rate had a great influence on the entropy generation of the reaction during hydration process.

7. Electronics Thermal Management

Recent development in wide-bandgap semiconductor and mini/micro- scale electronic technology has led to a drastic rise in power density for high-performance electronic devices and circuitry. However, the continuous miniaturization of electronic applications leaves a narrowing space for heat dissipation. Further, the temperature distribution is getting highly non-uniform as peak heat flux near the transistor gate can be 10 times that of the die area. Thermal management to improve reliability and prevent thermally induced failure of electronics is of paramount importance. Conventional cooling approaches are not capable of dealing with the high heat flux of emerging electronics. Therefore, considerable research focuses on novel and compact cooling techniques targeted for advanced electronics with extreme heat-flux, including heat pipe, embedded microchannel, impingement, thermoelectric cooling, immersion cooling, hybrid methods and incorporation of high-thermal-conductivity material.

In this section, the studies on heat transfer enhancement techniques applied to thermal management in modern electronic devices are reviewed due to the growing interest, critical challenge, and great practical significance.

7.1 Heat Pipes

Heat pipes are broadly used as an effective cooling solution for thermal management of miniature and ultra-slim mobile electronic devices. The heat pipe is a two-phase flow heat transport device utilizing capillary pressure of working fluid and the latent heat of the vaporization to aid heat transfer. Chen et al. (2020b) experimentally investigated heat transfer characteristics of gravity heat pipes (GHPs) with internal helical microfins (IHMs) of different arrangements and found applying IHMs could lower operating temperature and thermal resistance in comparison with smooth GHPs. Shioga et al. (2020) fabricated an ultra-thin flattened loop heat pipe with an 0.6-mm thick evaporator by using chemical-etching and diffusion-bonding process on thin copper sheets to eliminate the backflow of vapor to the liquid line and obtained a thermal resistance value of 0.11 KW^{-1} between the evaporator and the condenser at heat input of 20 W. A novel band-shape spiral woven mesh (SWM) wick was developed to enhance the thermal performance of ultra-thin flattened heat pipe (UTFHP) for cooling smartphones (Zhou et al., 2020d). UTFHP is fabricated by flattening cylindrical heat pipes; thus, the external surface area is limited, and its shape can only be a simple strip. In contrast, ultra-thin vapor chamber (UTVC) can be arbitrarily designed in shape and provide geometry flexibility. A UTVC with spiral woven meshes and one bottom mesh composite wick was designed, and its maximum effective thermal conductivity was found to be about 20900 $Wm^{-1}K^{-1}$ in horizontal state and 25200 $Wm^{-1}K^{-1}$ in gravity state (Huang et al., 2020b). Bahmanabadi et al. (2020) experimentally examined the effect of structured evaporator surface on the thermal performance of a thermosyphon heat pipe. They found the average thermal resistance reduction for heat pipes with radially rectangular-grooved and radially inclined triangular-grooved evaporator is 21% and 33%, respectively, compared with baseline design with smooth evaporator surface. Gupta et al. (2020) investigated the effect of CuO/water nanofluid on the thermal performance of a heat pipe for a wide range of input power (50−150 W) and inclination angle (0-90 ºC) .The experimental findings demonstrated 20.5% decrease in thermal resistance and 15.3% increment in thermal efficiency of the heat pipe compared to pure water.

7.2 Other Methods

Van Erp et al. (2020) presented an innovative approach for co-designing microfluidics and GaN-on-Si electronic power device by turning the passive silicon substrate into a near-junction liquid-cooled heat sink targeted for the hotspots. They proposed a 10× manifold microchannel design that could allow heat flux up to 1723 Wcm^{-2} for a maximum temperature rise of 60 K with an unprecedented coefficient of performance. Kewalramani et al. (2020) tested the thermohydraulic characteristics of micro heat sinks with short micro pin fin of different shapes (square and elliptical) and different arrangements (interrupted and staggered) and found the pin fin shape had a more significant effect on the thermal resistance compared to the arrangement of pin fin. Two-phase performance of a hybrid jet plus two-layer multipass microchannel heat sink using HFE-7100 as the coolant was investigated and heat flux up to 174 Wcm^{-2} was successfully dissipated at a flow rate of 450 ml/min (Joshi et al., 2020). Wei et al. (2020a) demonstrated the design, modeling, fabrication and characterization of a 3D printed direct liquid micro-jet array impingement cooler applied to a lidless dual-chip module and obtained a very low thermal resistance of 0.26 cm^2KW^{-1} at cooler flow rate of 1000 ml/min. Hashim et al. (2020) implemented free-surface circular water jet impingement cooling on a heated horizontal SS-304 plate (78 × 78 × 13 mm^3) in high temperature (500-900 °C) and explored the rewetting phenomenon. Luo et al. (2020a) carried out numerical simulations to investigate the effect of target surface curvature and the nozzle-to-target surface distance on the flow and heat transfer characteristics in a pin-finned double-wall structure for turbine cooling application. Lin et al. (2020) combined thermoelectric cooler (TEC) with microchannel heat sink (MHS) using TiO_2/water nanofluids as the coolant for cooling of high-power light-emitting diode (LED). The nanofluid-cooled TEC-MHS system exhibited effective performance in the thermal management of the 50-W LED. Electrically insulating printed circuit board (PCB) and electronic devices from the water by Parylene C coatings (as thin as 1 um), Birbarah et al. (2020) implemented water immersion cooling strategy on a 2-kW power converter and observed a large footprint-area-averaged heat flux value (up to 562 Wcm^{-2}).

7.3 High Thermal-Conductivity Materials

Applying high-conductivity materials such as diamond, CNTs and graphene to enhance heat transfer in high-end electronics and equipment is an active research area of major interest. For example, they can be mixed with a matrix substrate or used solely as a heat spreader to enhance conduction or be added as nanoparticles into the base coolant to assist convection. Diamond was used as both the coating layer and substrate in AlGaN/GaN high-electron-mobility-transistors (HEMTs) to remove the large heat flux (Zhang et al., 2020c). Alshayji et al. (2020) experimentally evaluate the thermophysical properties of diamond/water nanofluid over different ranges of temperature (20-60 ºC) and solid concentrations (0.125-1.25 vol%) and achieved a maximum enhancement in thermal conductivity by 25%. Thermally reduced graphene oxide/carbon nanotube (rGO/CNT) composite films were successfully prepared by high-temperature annealing process and showed great potential as a TIM for thermal packaging applications due to their high in-plane thermal conductivity and good mechanical properties (Yuan et al., 2020). Ong et al. (2020) investigated the thermal performance of graphene oxide (GO) nanofluids in a microchannel at different inlet flow rates (0.5-2 mL/min) and set temperatures (50-90°C). It was found that minor addition of GO nanoparticles (0.02-0.1 wt.%) could remarkably enhance the thermal conductivity of GO-NFs, whereas the viscosity increase was not significant, demonstrating the great potential of GO nanofluid in miniaturized device thermal management. Kim et al. (2020) introduced a heat-dissipating hybrid film coated with carbon nanotubes (CNTs) entangled with silver nanowires (AgNWs), prepared by supersonic spraying, to address hotspots in portable electronics and obtained ~34% improvement in effective heat transfer coefficient, compared with that of the bare substrate. Hybrid nanofluids were prepared using nanocomposites (graphene/Al_2O_3) with various graphene concentrations (5–50 wt.%) and results showed that the thermal conductivity enhances to a maximum of 45% (±3%) compared to base fluid deionized water (Selvaraj and Krishnan, 2020). Gan et al. (2020) integrated graphene nanocapillaries into a micro heat pipe (MHP) for enhanced LED cooling, demonstrating over 45% enhancement in the overall thermal performance than the uncoated counterpart.

8. Prospects

In recent years, environmental protection and energy conservation have become crucial issues due to greenhouse warming caused mainly by the use of fossil fuels. One of the fundamental ways of mitigating carbon emissions is to increase the efficiency of energy conversion devices. Enhancing the performance of a heat transfer device is therefore of great interest since it can result in energy, material and cost saving. Research of innovative heat transfer enhancement techniques is immense, encompassing every aspect from understanding the fundamental theory and physical mechanisms of various heat transfer enhancement techniques to designing the heat transfer enhancement devices and evaluating these devices in industrial practice. Research of emerging heat transfer enhancement techniques used in thermal power engineering, energy storage, high performance heating and cooling technology such as using nanofluids, micro- and nano-structures, microchannels to enhance heat transfer and new compound enhancement techniques incorporating these new and conventional techniques becomes popular over the past years. However, there are also big challenges in achieving agreed heat transfer performance, physical mechanisms, theory, prediction methods and engineering design methodology and practical applications with these emerging techniques. Therefore, many aspects are needed to be investigated and developed.

With the increasing energy demand in the development of technology and economy progression in the modern world, energy storage is essential not only because it can reduce the supply-demand energy gap, but also because it can improve the performance in energy conservation and reduce generation cost. PCM is one of the most appropriate and prospective materials for effective thermal energy storage from renewable energy resources, as PCMs have high energy density, strong stability of energy output, and appropriate working temperature range. Therefore, PCMs have gained a wide range of applications in various fields, such as buildings, solar energy systems, power systems, and defense industry. However, the low thermal conductivity of PCMs limits its applications in the field of LHTES system. In order to overcome this issue, demand of innovative methods for enhancing heat transfer on PCMs is increasing.

TES based on PCMs will get more attention in the next decade, and more and more researchers will focus on this area. Future research will have an emphasis on the conductivity enhancement based on NEPCMs and nanoparticle additive PCMs, or combined, on thermal energy storage from solar energy and other renewable energy. PCMs energy storage systems can be designed based on the existing experimental data. High temperature (>1000 °C) energy storage systems can also be studied and developed. Potential applications include thermal management system on the electrical vehicles and grid energy storage system based on concentrated solar power.

TES based on NFs will also attract more interest in the next decade. The main limitation of NF is its instability during synthetic and operational processes. Many researches only focused on either the single factor of synthetic conditions, like size, shape, concentration, etc.; or the single factor of operational conditions, like temperature, composition, shear, magnetic field, etc. A systematic study considering all operational conditions is necessary for future work. More turbulent flow analysis of NFs is also needed. As some of the classic models of NFs are proved to be not precise, machine learning methods like the Artificial Neural Networks (ANNs) can be applied to predict the thermodynamic properties of NFs.

Heat exchanges are widely used in industrial applications, such as air conditioning, power stations, chemical plants, petroleum refineries, sewage treatment, cooling of turbine and internal combustion engine, wasted heat recovery and etc. The type, size and configuration of exchanger should be tailored and carefully selected to improve the system performance and save expense. Enhanced performance in heat exchangers can be achieved through inserting tapes, integrating fins, adopting helical baffles, utilizing nanofluids, optimizing system configuration and leveraging two-phase flow, while these techniques will add system complexity, increase equipment cost and impose challenges on the operational stability. Only by considering practical operation issues, such as manufacturing difficulty of inserted tapes, nanofluid compatibility, pressure instability in two-phase flow, can ensure the successful deployment of the heat exchanger to aid heat transfer.

It should be emphasized that nanofluids and PCMs can be applied in a wide range of heat transfer enhancement technologies, while more research is needed to address the practical issues, such as the proper dispersion of nanoparticles, long-term stability, agglomeration, and sedimentation and their effects on the alteration of optical, radiative, and thermal-fluid properties.

Trend of miniaturization and 2.5D/3D packaging in the semiconductor industry has resulted in large heat flux constrained in narrow space for electronic devices. What's worse, the heat flux is getting highly nonuniform with peak heat flux ten-fold that of the background heat flux. Most likely, we will see more and more compact cooling techniques targeted for advanced electronics with extreme heat-flux, including ultra-thin heat pipe, embedded microchannel, near-junction impingement, thermoelectric cooling, immersion cooling, hybrid methods and incorporation of high-thermal-conductivity material. Besides, co-designing electronics with cooling techniques is a prospective research direction, which will bring functional performance of devices to the next level and save energy consumption.

For effective dissipation of extremely high heat flux generated in high-power electronics devices and high-end equipment, boiling heat transfer is an ideal choice and current technologies have not realized its theoretical limit yet. New emerging research on boiling and condensation phase-change heat transfer enhancement using micro- and nano-technology is in great need. In particular, it calls for more experimental investigations to reveal the fundamental nanoscale boiling and condensation enhancement mechanisms. Nonetheless, manufacturing challenges, new materials, new working fluids, and long-lasting issues must be explored. Phase-change heat transfer enhancement based on nanostructured engineering is also critical for resolving surface icing/fogging/frosting problems in engineering systems and natural environment.

The first-principles methods based on density functional theory and Boltzmann transport equation provide well prediction for single crystals. For the thermal investigation of defects at interfaces and nanostructures in near junction heat transfer, the MD and Monte Carlo method could provide an efficient way into heat conduction physics. Machine learning for micro- and nano-scale modelling of heat conduction may be a fruitful direction to pursue, especially for phonon transport at amorphous materials, as well as the structural design of maximized/minimized thermal resistance of superlattices. With the rapid development in first-principles simulation methods, computing the interactions between electrons, phonons, photons, isotopes and grain boundaries has become possible. These advancements would strengthen the understanding of interfacial heat conduction, and further facilitate the optimization of thermal, electrical and optical properties for future multifunctional materials.

Near-field radiative heat flux can exceed the far-field blackbody limit, as governed by the Stefan-Boltzmann law. Fundamental understanding of near-field radiation at extreme gap spacing will help enable high-power-density and high-efficiency conversion of heat to electricity in thermophotovoltaic (TPV) systems. More experimental studies and demonstrations are needed, but fabricating and maintaining a near-field optical gap is still a challenge.

Solar energy is a vast, inexhaustible, and clean resource, which can be used for heating and lighting homes, generating electricity, desalination, and a variety of other commercial and industrial uses. Conventional solar energy usage has grown over the years but its expansion still faces limitations such as high cost, climate dependence, and large space coverage. Research will continue to focus on improving the system efficiency and reducing the cost of solar energy harvest, storage, and conversion.

Passive, active and compound techniques in convective heat transfer enhancement have been explored for decades; and thus, it might be difficult to achieve some significant breakthrough in a single piece of work. Nevertheless, it calls for more experimental investigations and applications in thermo-fluid and energy systems and other engineering practices. Another direction for comprehensive research could be the integration of empirical correlations, theoretical models, and experimental measurements with emerging machine learning tools on modified surfaces and geometries such as twisted, corrugated, and dimpled ones or with coiled wire inserts.

Both conventional and emerging heat transfer enhancements are crucial in achieving zero carbon target by 2025. From the literature survey, there are big challenges in heat transfer enhancement research but also new opportunities to developing innovative technologies in energy, renewable energy and zero carbon industrial and civil applications. Many aspects of conventional and innovative heat transfer enhancement techniques such as systematic theory, mechanisms, materials, design methodology and engineering applications are fast developing and needed to be achieved.

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