AN OVERVIEW OF HEAT TRANSFER ENHANCEMENT LITERATURE IN 2019

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Advances in modern technology with increasing power density call for new technologies of heat transfer enhancement. This article briefly reviews archival journal literature on enhanced heat transfer research and development published in 2019 in the English language. Since a large number of articles were published, the selected studies are focused and grouped into conduction, convection, radiation, phase-change materials energy storage, and high-performance heat exchange devices. The methodologies for enhancing convective heat transfer are further categorized into passive, active, and compound techniques. The review on heat conduction focuses on the micro/nanoscale aspects, interfaces and high-conductivity carbon materials. The emphasis of thermal radiation is on near-field radiation, solar energy, and metamaterial. Recent progress in applying machine learning to enhanced heat transfer research in nanofluids, solar energy, and heat exchangers is also discussed.

KEY WORDS: *enhanced heat transfer, conduction, convection, radiation, energy, phase-change material, nanoscale, nanofluid, interface, machine learning*

1. INTRODUCTION

Following the brief review on heat transfer enhancement literature published in 2018 (Guo, 2019b), the present overview continues to circumscribe the enhanced heat and mass transfer peer-reviewed papers published in 2019 in archival journals in the English language. In the past year, considerable effort has been devoted to research on heat transfer augmentation. Because the publication amount is huge, selection is certainly inevitable. In many situations, dozens, hundreds, or even thousands of publications involve in a narrow research topic, but only a few selections have been incorporated into this review. For example, a topic search in the Web of Science (accessed on January 27, 2020) returned over 4000 papers involving in nanofluid research and development; and over half of which are relevant to improving thermal properties or intensifying heat transfer processes.

Heat transfer enhancement refers to the improvement of thermal performance of any heat transport process, heat exchanging medium, component, device, equipment, or system. It could mean that the thermal conductivity or diffusivity of a substrate is amplified, the heat transfer rate of a given surface is increased, the peak temperature of a chip hot spot is reduced, the critical heat flux for pool boiling heat transfer is raised, the specific heat capacity or latent heat of an energy storage medium is ameliorated, the thermal performance of a heat exchanger is improved, the solar radiation absorption efficiency of a solar energy system is enhanced, etc. As devices in modern technology continue to require increased power capabilities with reduced spatial profiles, it is critical to explore a multitude of methods for augmenting heat transfer. In a recent open letter (Guo, 2019a), the editor-in-chief of *Journal of Enhanced Heat Transfer* called for expansion of the journal scope to incorporate the latest development and trends of research in this field. Heat transfer intensification is now a major area of research and development in thermal management, electronic components and devices, packaging technology, energy and power industry, new building technology, engines, aerospace and defense technologies, and other relevant engineering areas.

2. HEAT CONDUCTION

The present review focuses on the literature for heat conduction enhancement in the micro/nanoscale, particular in interfaces and high-conductivity carbon materials in various forms (i.e., carbon nanotube (CNT), graphene, and diamond).

2.1 Interfaces

With the rapid development of miniaturization, pursuing heterogeneous integration to create advanced functionalities with large amount of heat dissipation has become a formidable challenge. Interfaces between dissimilar materials can impede heat transfer and create thermal resistance and heat accumulation. A low-resistance interface is crucial and highly demanded. For high-power and high-frequency devices, phonon transport in heterogeneous structures is the key for heat dissipation. A recent work reported the temperature-dependent measurement on thermal conductivity of β-$(Al_{0.1}Ga_{0.9})_2O_3/Ga_2O_3$ superlattices (Cheng et al., 2019b), in which a significant reduction in thermal conductivity (5.7 times reduction) at room temperature was observed compared to bulk Ga_2O_3. Based on molecular dynamics (MD) simulations, Feng et al. (2019) reported that atomic layers near the interface are dominated by interfacial modes, which act as a bridge that connects the bulk Si and Ge modes. Such bridging effect boosts the inelastic transport to contribute more than 50% to the total thermal conductance at room temperature. These phonon modes are in strong thermal nonequilibrium near the interface, which impedes the thermal transport. Ghodke et al. (2019) found an energy-filtering effect at grain boundaries of the re-substituted higher manganese silicide $Mn_{30.4}Re_6Si_{63.6}$. They observed a reduction of the thermal conductivity to very low value of 1.27 $W \cdot m^{-1} \cdot K^{-1}$. Van Roekeghem et al. (2019) quantified the thermal resistances of GaN/AlN graded interfaces of varying thickness using *ab initio* Green's functions and compared them with the abrupt interface case, showing that the overall behavior of such graded interfaces is very similar to that of a thin film on the length scales relevant to real interfaces. Lindsay et al. (2019) reviewed the development of phonon thermal transport from defects, disorders, MD simulations, Peierls–Boltzmann transport calculations, and machine learning aspects. Varnavides et al. (2019) introduced a ubiquitous Si–Ge semi-coherent interface and confirmed that nonintrinsic phonon scattering near the interface plays a dominant role in thermal interface resistance. Rastgarkafshgarkolaei et al. (2019) proposed a strategy to enhance interfacial thermal transport through solid–solid interfaces by adding nano-engineered, exponentially mass-graded intermediate layers. Their analysis showed that the effect on thermal conductance is dominated by the phonon thermalization through anharmonic effects, while elastic phonon transmission and impedance matching play a secondary role.

2.2 Nanoscale Heat Transfer

As structures and devices shrink to the nanoscale, it requires developing novel physical insights into the nature of phonon transport. The *ab initio* theoretical tools such as those based on first-principles density functional theory (DFT) have been recently developed and demonstrated their capability to precisely calculate thermal properties of materials (Fan et al., 2019). Xu et al. (2019b) used first-principles simulations to study thermal transport in SiGe alloys and showed the effect of electron–phonon interaction on lattice thermal conductivity. Malhotra et al. (2019) demonstrated the need for quantifying the impact of all relevant length variables in superlattices, i.e., the mean free path and wavelength of phonons, the periodicity of the structure, total size of the superlattice, and the length scale of interfacial disorder, to fully understand the heat conduction in superlattices. Polanco and Lindsay (2019) computed the vibrational thermal conductance across GaN–AlN interfaces using nonequilibrium Green's function in the harmonic limit and interfacial interatomic force constants (IFCs) fully from DFT. The effects of supercell size, the enforcement of symmetry constraints, and truncation of IFCs, and atomic relaxation on phonon transmission and conductance were explored.

As an alternative simulation method based on Newton's equations of motion, MD can achieve a relatively larger scale of simulation compared to the first principles methods. Diaz and Guo (2019) employed MD simulations to understand the thermal conductivity and pool boiling enhancement via adding a single-layer graphene to graphene-compatible substrates such as Cu, Ni, Pt, and Si. Liu et al. (2019b) reported that both doping and interface topography optimization could effectively increase the interfacial thermal conductance (ITC) and the overlap of the phonon density of states (PDOS) of a graphene/h-BN 2D-heterostructure. Li et al. (2019c) studied black phosphorus, a 2D material with highly anisotropic interfacial thermal boundary resistance (TBR). They concluded that the highly anisotropic TBR could be attributed to the intrinsic band structure and phonon spectral transmission. Their MD simulations showed consistency with experimental results. Rajabpour et al. (2019) studied carbon nitride and concluded that 2D nanostructure with higher thermal conductivity has a lower value of interfacial thermal conductance with the silica substrate. A recent work calculated the lattice conductivity of single- and multilayer pristine MoS_2 using different empirical potentials. The reactive empirical bond order (REBO) potential gave the most reasonable predictions and isotope scattering has only a small effect on thermal conductivity of MoS_2 (Xu et al., 2019a).

Ohnishi and Shiomi (2019) reviewed briefly the impedance of phonon transport with nanostructures and their interfaces and revealed that aperiodic nanostructures can effectively reduce thermal conductivity and consequently improve thermoelectric performance. A method of controlling and tuning heat transport across an interface was proposed by Cheng et al. (2019a), in which the diamond–silicon thermal boundary conductance and thermal conductivity increased by 65% and 28%, respectively, of the diamond layer grown on the nanostructured substrate compared with that of a flat substrate. Jeong et al. (2019) examined the cross-plane thermal conductivity of $SrRuO_3$ thin films and found that the 34-nm-thick and 8-nm-thick films have respectively 62% and 25% of the thermal conductivity compared to the bulk value. This is attributed to the short mean free path of the thermal carrier which is estimated to be about 20 nm in the bulk state. Kim et al. (2019) reported a fabricated microdevice to measure the ballistic thermal resistance of a constrained silicon film, in which the frequency dependent Boltzmann transport equation (BTE) was numerically solved for a 3D model using finite element analysis combined with the discrete ordinate method and the frequency dependence of phonons. Zhao et al. (2019b) found that structure defects in kinks of Si nanowires can assist phonon transport through the kink. Zobeiri et al. (2019) developed a new Raman probing technique for measuring the thermal conductivity of suspended nm-thick materials.

2.3 Carbon Nanotube (CNT), Graphene, Diamond

High-conductivity carbon materials such as 1D CNTs, 2D graphene, and 3D diamond have been a major interest of research for enhancing heat conduction in micro/nanoscale components and devices or in high-end electronics and defense products. For example, they are commonly used as the filler structure to boost the thermal performance of a matrix substrate for rapid cooling and thermal management of modern electronic devices characterized by exploding power dissipation and shrinking size. Qiu et al. (2019b) made a novel structure of pristine CNT fibers decorated with Au nanoparticles and an impressive boost in the interfacial thermal transport (up to 70%) was acquired. CNTs were isolated from 3D nanopillar graphitic structure and measured with a thermal four-probe method to obtain the intrinsic thermal conductance (Fleming et al., 2019). Limited thermal conductivity of graphene-based polymer composites is found, despite of the extremely high thermal conductivity in the range of 3000–5000 $W \cdot m^{-1} \cdot K^{-1}$ along the basin plane of graphene. A continuous network of graphene foam (GF), filled with aligned graphene nanosheets (GNs) is shown to be an ideal filler structure and the synergistic effect between the aligned GNs and 3D interconnected GF on improving the thermal conductivity for the composite has been explained and analyzed (Wu et al., 2019b). Xin et al. (2019) reported an optimized structure with tunable graphene sheet alignment and orientation, obtained via microfluidic design, enabling the manufacturing of macroscopic graphene with superior thermal properties. Unique Ag nanoparticles anchored reduced graphene oxide (Ag/rGO) fillers with the "point-plane" structure were successfully fabricated by employing a "one-pot" method and the thermal conductivity value of the Ag/rGO/polymide nanocomposites reached a maximum of 2.12 $W \cdot m^{-1} \cdot K^{-1}$, about 8 times as high as the pure polymide (Guo et al., 2019). Mashali et al. (2019) reviewed recent developments in improving the thermal conductivity of fluids by the addition of diamond nanoparticles and discussed its potential application in automotive, electronics, and cryosurgery industries. Void-free interfacial copper matrix composites reinforced with diamond particles of various diameters were prepared via composite electroplating and the results show the Cu–diamond composite reinforced with large diamond particles (400 μm) possesses high thermal conductivity of 846.52 $W \cdot m^{-1} \cdot K^{-1}$, serving as a promising heat sink material in microelectronic industry (Wu et al., 2019a).

3. CONVECTION

Convective heat transfer enhancement can be categorized by passive or active techniques which cover various ideas focusing on either solid surface, in fluid, or with combined effects-compound technique.

3.1 Passive Techniques

3.1.1 Surface Modification

Surface modification techniques here include use of extended surfaces or fins, treated surfaces, rough surfaces, etc. Han and Yu (2019) assessed the flow and heat transfer performance of a corrugation channel to reveal the heat transfer enhancement mechanism. Guan et al. (2019) measured the Nusselt number in hydrophobic micro pin fin heat sinks with different contact angles. Kim (2019) tested steam condensation on titanium corrugated tubes and significant enhancement of condensation heat transfer was noted. Fouling control using sponge balls was also examined. Yilmazoglu et al. (2019) simulated the effects of fin spacing, fin thickness, base thickness, and heat sink positions on an electronic driver unit of an HVAC system. Menni et al. (2019) investigated the effects of baffle shapes on the thermal aerodynamic performance of a rectangular channel with wall-mounted baffles and fins. Gaur et al. (2019) derived a novel surface roughness element from the combination of dimple and protrusion elements and looked into the thermal and flow characteristics of a rectangular channel with such a surface element. Dong et al. (2019) developed the volume of fluid model to simulate the subcooled flow boiling on the heating surface with different cavity configurations in a horizontal cooling passage under engine-like condition. Mondal and Kim (2019) tested nucleate boiling enhancement on surfaces having circular pores and rectangular subtunnels. Bhavnani et al. (2019) described the use of microscale asymmetric surface patterns in the form of an array of ratchet structures to generate preferential fluid motion during boiling heat transfer. Sharma et al. (2019) used transient liquid crystal thermography to acquire the local heat transfer coefficients of a rectangular duct with periodic trapezium ribs and found that most of the trapezium ribs provided a better overall enhancement than the square ribs. Experiments were conducted to study the effect of dimples on fins, fin thickness, and fin height on air-side heat transfer enhancement and to evaluate the penalty of pumping power for elliptical tube cross flow heat exchangers (Wolk and Dhir, 2019). Nirgude and Sahu (2019) measured a maximum of 219% enhancement in the boiling heat transfer for laser-processed copper surfaces compared to plain surfaces and revealed that the cavities inside the channels/grooves act as active nucleation sites and the channels/grooves provide a liquid path to the nucleation site, delaying a dry-out condition. An experimental work has reported for condensate retention/retention angle of water on pin fin tubes of varying circumferential fin spacing and fin thickness (Ali et al., 2019). Naderi et al. (2019) experimentally investigate the thermal-fluidic performance of a three-layered unit cell stack for supercritical carbon dioxide (sCO_2) power cycles, in each unit cell the sCO_2 flows through a microscale pin-fin array on the hot and cold sides. Zarringhalam et al. (2019) reported that the addition of roughness elements on a microchannel could extend contact surfaces of energy transfer and empower boiling process.

3.1.2 Devices, Inserts, and Coiled Tubes

Nalawade et al. (2019) reported the experimental results for friction factor and heat transfer coefficients for flow through a square duct with delta wing vortex generators. Patil et al. (2019) conducted experimental measurements on a heat exchanging tube fitted with circular rings, with a circumferential gap between the ring and inner wall of the tube as well as rings in the wall-attached position. Circular rings were selected to achieve flow blockage. The insert with a circular ring of 50% flow blockage area and 1-mm gap was found to give the highest enhancement (3.51 times) in the rate of heat transfer compared to the smooth tube at higher Reynolds number. Emani et al. (2019) experimentally studied the effects of coiled wire inserts of various cross sections on the heat transfer intensification and friction factor characteristics of air flow through a horizontal pipe and developed a set of empirical correlations. Godbole and Ramakrishna (2019) observed that the curved and U-shaped tube had the larger number density of helices near the inlet, leading to higher temperature separation and subsequently cooling capacity in a vortex tube. To enhance the cooling of high-temperature calcined petroleum coke inside a cooling water jacket, Wu et al. (2019c) installed heat exchange tubes inside the water jacket. Zhao et al. (2019a) proposed an innovative wasp waist tube for improving the air-side thermal-hydraulic performance of the assembled compact fin-and-tube radiator. Gunes and Karakaya (2019) experimentally examined the thermal and flow resistance characteristics in a tube equipped with loose-fit perforated twisted tapes. Corrugated strip elements were placed axially at circular channel center to enhance heat transfer (Altun et al., 2019).

3.1.3 Additives and Nanofluids

Cakmak (2019) prepared homogeneous and stable aqueous boric acid with a probe sonicator and examined the impacts of boric acid concentration and temperature on thermal conductivity. Akash et al. (2019) carried out an experimental evaluation of thermohydraulic performance of water/ethylene glycol-based graphite coolant in vehicle radiators, in which the overall heat transfer coefficient was found to be augmented with the use of the nanofluid coolant. Contreras et al. (2019) also investigated the thermohydraulic performance in automotive radiators with a nanofluid coolant of graphene and silver nanoparticles with water and ethylene glycol (50:50 vol.%) as a base fluid. Shinde et al. (2019) scrutinized the deterioration in thermal conductivity of nanofluid with regard to time and observed nanoparticle clustering and breaking after the 200-h test duration. Shahriari et al. (2019) studied natural convection of an Al_2O_3/water nanofluid using the Lattice Boltzmann method. The effect of wavy-surface geometry parameters, such as the wavelength and amplitude ratio, on heat transfer was also examined. Dagdevir et al. (2019) simulated aqueous Al_2O_3 nanofluid flow through various chamfered ducts of square cross section. Kaya et al. (2019) analyzed entropy generation caused by heat transfer and friction of forced convection flow in a semicircular cross-sectioned microchannel with TiO_2/water nanofluid. An experimental investigation was conducted to quantify the heat transfer coefficient, friction factor, pressure drop, pumping power, and thermohydraulic performance index in a microchannel with aqueous graphene nanoplatelet nanofluids (Sarafraz et al., 2019).

Nanofluids have very complicated thermophysical properties and nonlinear thermal hydrodynamic characteristics. Machine learning (ML) could be a better tool for advancing nanofluid heat transfer research because of its ability to handle a large number of complex, interrelated data. ML methods include artificial neural network (ANN), group method of data handling, adaptive neuro-fuzzy inference system, category and regression tree, support vector machine, etc. Bahiraei et al. (2019a) reviewed ML algorithms used for prediction and optimization of thermal properties of nanofluids. Ramezanizadeh et al. (2019a) provided a review on ML methods for predicting dynamic viscosity. The input variables could include temperature, pressure, NP volume fraction or mass fraction, NP type, base fluid type, etc. The output variables could be thermal conductivity, dynamic viscosity, specific heat, radiation absorption, etc. The current database for ML is still limited.

3.1.4 Porous Media

In the study of ferrofluid flow through a porous medium under the impact of Lorentz force, Sheikholeslami (2019) found that the exergy loss augments with enhancement of Lorentz force and Bejan number increases with increasing permeability and Rayleigh number. A coupled mode of electromagnetic, heat transfer, and multiphase porous media was built to study microwave heating in coal processing (Li et al., 2019b). The lattice Boltzmann (LB) methods applied to single-phase and solid–liquid phase-change heat transfer in porous media were reviewed (He et al., 2019b). LB methods are controversial in that their benefit in the context of solving heat transfer enhancement problems might be limited for phase-change problems. Arqub and Shawagfeh (2019) applied the reproducing kernel algorithm for solving Dirichlet time-fractional diffusion-Gordon types equations in porous media.

3.2 Active Techniques

3.2.1 Mechanical Aids, Surface or Fluid Vibration

The concurrent use of Al_2O_3/water nanofluid and transverse oscillation in a heated circular cylinder was numerically investigated by Mousavi and Heyhat (2019). Results showed that using alumina/water nanofluid is more effective than the oscillation of cylinder for heat transfer enhancement in cross-flow in the range of studied parameters. Błasiak and Pietrowicz (2019) analyzed heat transfer enhancement in a disturbed thermal layer via mechanical aids and validated their numerical model with experimental data. Sarhan et al. (2019) inspected vibration effects on thermal performances of the rectangular flat plate under natural convection condition in both horizontal and slightly inclined from horizontal orientations at multiple angles. Vjatkin et al. (2019) claimed that vibration is an effective tool for heat transfer enhancement in rotating cavity and resonant excitation of inertial liquid oscillations intensifies heat convection.

3.2.2 Electro-Magnetic Fields

Rauf et al. (2019) numerically studied the unsteady oscillatory magnetohydrodynamic (MHD) flow of a viscous liquid over a rotating oscillatory disk and found that the increase in the magnetic parameter degraded the flow amplitude. Kumar et al. (2019a) outlined the impact of induced magnetic field and thermal radiation on magnetic-convective flow of dissipative fluid. Ramesh and Prakash (2019) analyzed heat transfer enhancement in MHD pumping of electroosmotic non-Newtonian physiological fluid through a microfluidic channel, exploring peristaltic transport as symbolized by heat transport in biological flows, novel pharmacodynamics pumps, and gastrointestinal motility enhancement. Khosravi et al. (2019) demonstrated that using magnetic field can augment heat transfer in ferrofluids for a parabolic trough solar collector, thermal efficiency as well as output temperature of the collector.

3.2.3 Injection or Suction

In a study by Shi et al. (2019a), liquid N_2 was injected into goaf to decrease temperature and prevent spontaneous combustion during mining operation. The effect of inclined jet impingement on circular pin-fin heat sinks with or without a hollow perforated base plate was experimentally investigated by Wen and Ho (2019). An experimental study of mist jet impingement cooling over a heated flat surface was carried out to inspect the effects of Reynolds number, nozzle-to-plate spacing, and mist loading fraction; and a correlation was developed (Chauhan and Singh, 2019). Lily et al. (2019) achieved augmentation of heat flux in transition boiling regime at high temperature by using low mass flux spray. These studies demonstrate that injection or suction techniques may achieve substantial increase in heat transfer rate.

3.3 Compound Techniques

Many studies used a combination of passive and active enhancement techniques. Zhang and Chen (2019) carried out an experimental research on submerged jet impinging boiling of a brass beads-packed porous layer to understand the impact of such an internal porous structure on the onset of nucleate boiling and critical heat flux. Ligrani et al. (2019) investigated winglet-pair target surface roughness influences on impingement jet array heat transfer, relating performance to different roughness element arrangements as well as to target surface internal conduction and to the increased transport and mixing produced by arrays of the roughness elements. Nayak and Mishra (2019) considered the ultrafast cooling method based on nanofluid impingement and the overall improvement in cooling rate was found to be 19.34%, 11.3%, and 7.14% using TiO_2, Al_2O_3, and CuO nanofluids, respectively, over the conventional water spray. Fard et al. (2019) measured the heat transfer rate and pressure drop of CNT/water nanofluid in a helically coiled tube. An experimental work of the thermal hydrodynamic performance of a square channel with nanofluid and protrusion ribs was performed by Kumar et al. (2019c), evaluating the effects of a wide range of parameters including protrusion transverse rib roughness, nanoparticle concentration and diameter, streamwise pitch, spanwise pitch, relative print diameter ratio, and Reynolds number. Li et al. (2019a) numerically investigated the effects of the geometric parameters and heat flux on the thermohydraulic characteristics of microchannel heat sinks combined with ribs and cavities. Li et al. (2019e) studied forced convection of a nanofluid in a permeable enclosure under the effect of Lorentz forces and found that convective heat transfer augments with increase in the Darcy and Reynolds numbers but reduces with increase of a magnetic field. Bahiraei et al. (2019b) numerically examined the hydrothermal characteristics and energy performance of a triple-tube heat exchanger equipped with inserted ribs and a hybrid nanofluid containing graphene nanoplatelet–platinum composite powder. Abedini et al. (2019) inspected the effect of a baffle on free convection heat transfer of a water–Fe_3O_4 nanofluid in a C-shaped enclosure in the presence of a magnetic field.

4. RADIATION AND SOLAR ENERGY

In this section, the studies on special heat transfer enhancement techniques related to radiation heat transfer and solar energy applications are reviewed because of their unique cases and increased interests.

4.1 Radiation

A number of works explored the enhancement of thermal radiation in either the far-field or near-field during 2019. Elzouka and Ndao (2019) increased the number of channels by carving a variety of slots with different sizes to enhance thermal radiation. Barnoon et al. (2019) simulated two-phase natural convection and thermal radiation of non-Newtonian nanofluid in a porous cavity considering inclined cavity and size of inside cylinder. Prakash et al. (2019) numerically investigated the peristaltic pumping of magnetic nanofluids with thermal radiation and temperature-dependent viscosity effects. Yang et al. (2019c) conducted a research of turbulence radiation interaction effect on radiative heat transfer in a swirling oxyfuel furnace. Ruiz et al. (2019) experimentally and numerically analyzed the heat transfer in a packed bed exposed to the high thermal radiation flux. Bhatti et al. (2019) revealed the entropy generation on the interaction of nanoparticles over a stretched surface with thermal radiation. Niu et al. (2019) proposed a simplified model for fast estimating infrared thermal radiation of low-altitude underexpanded exhaust plumes.

Near-field radiation heat transfer enhancement using natural hyperbolic material was demonstrated by Salihoglu and Xu (2019). Shi et al. (2019c) enhanced the near-field radiation by applying the graphene/Si grating multilayer system. Elçioğlu et al. (2019) compared several III–V group compound semiconductors (mainly GaAs, InSb, and InP) to understand the effects of chemical and physical properties of surfaces and wafers on near-field radiation transfer in order to explore utilization of near-field radiation transfer in energy harvesting applications from fabrication point of view. Controlling the chemical potential of photons could lead to near-field thermal radiation cooling (Zhu et al., 2019). Based on three-body photon heat tunneling and the varied near-field radiative heat flux with surface plasmon polaritons of graphene, He et al. (2019a) theoretically demonstrated a near-field thermostat for thermal management and controlling temperature. Shi et al. (2019b) experimentally demonstrated the colossal enhancement of near-field radiation between two graphene-covered heterostructures through surface plasmon and phonon polaritons coupling. Papadakis et al. (2019) showed the enhancement of net heat transfer by the interaction of surface plasmon and phonon polaritons and proposed a thermal metal-oxide-semiconductor switch for actively controlling the near-field heat flux. Hao and Guo (2019) demonstrated the precise measurement and monitoring of superconductor temperature using an optical whispering-gallery mode sensor based on near-field photon tunneling and resonance.

4.2 Solar Energy

Environmental impacts of existing technologies due to human activities have never been so much focused in research globally due to its significant uncertainty to the future. The pollution caused by burning fossil fuel, and the safety issue of nuclear power generation contributes to the rise of alternative energy sources, such as renewable solar energy. Concentrated solar power (CSP) plants are expected to achieve low-cost commercial power generation in the near future. The performance of a CSP system depends on the thermal properties of the working fluid and the temperature of the thermal energy storage system (TES). Molten salts were widely considered as the heat transfer and TES material because of their low cost, high operation temperature range, and process efficiency promotion. However, their thermal conductivity and specific heat are worse than those of water or thermal oil. Some researchers have tried to increase the specific heat and thermal conductivity by the use of salt-based nanofluids (Navarrete et al., 2019; Fernández et al., 2019).

The efficiency of a solar collector is primarily affected by the solar radiation energy absorbing process and the heat transfer process from the absorber to the working fluid. Nanofluids are of high potentials to boost the efficiency of solar collectors by improving the solar irradiation absorption and heat transfer processes. Sharafeldin et al. (2019) examined a different volume fraction of Cu–water nanofluid that plays an important role to enhance the solar energy absorption and the removal of the stored thermal energy. Nazari et al. (2019) examined the performance of Cu_2O nanofluid in single slope solar still with thermoelectric glass cover cooling channel. Jouybari et al. (2019) used SiO_2/deionized water as a working fluid to enhance the thermal performance of a flat plate solar collector. Sarafraz et al. (2019) used carbon nanoparticles in acetone as a nanofluid to enhance the thermal performance of evacuated tube solar thermal collectors. Shah and Ali (2019) provided a comprehensive review on application of hybrid nanofluids in solar radiation with practical limitations and challenges.

Kumar et al. (2019b) modified the heat-absorbing side of a solar air heater with ribs to improve the performance. Rezaei et al. (2019) examined combination of carbon dots and TiO_2 for enhancing the dye-sensitized solar cell's power conversion efficiency. A novel air source hybrid solar-assisted heat pump system with finned tube evaporator and collector evaporator can efficiently enhance the performance of heat pump (Cai et al., 2019). Jian et al. (2019) demonstrated that doping of alkali metal (Li, Na, K, Rb, Cs) ions improves the optical and electrical properties of Sb_2S_3, which is a stable light harvesting material for solar cells. Peng et al. (2019) proposed a novel c-Si based building integrated photovoltaic (BIPV) laminate and evaluated the overall energy performance of the BIPV insulated glass unit including power, heat, and daylighting. Cai and Guo (2019) realized spectral tuning for simultaneous solar energy harvest and visible light natural illumination using a water-filled prismatic louver. Cheng et al. (2019c) investigated the temperature distribution of the molten salt flowing in a solar tube receiver with/without considering radiative transfer. Yang et al. (2019a) optimized the spectral solar radiation selective absorbing coating for parabolic trough receiver. Kashyap et al. (2019) integrated the molecular and phase-change hybrid material system to simultaneously harvest and store solar irradiation energy.

The utilization of nanofluids usually is accompanied with the increment of viscosity and pressure drop penalty. For a more comprehensive analysis of the system performance and determining the optimal conditions, ML methods again can be applied for modeling and optimizing nanofluid-based solar energy systems, such as in studies by Delfani et al. (2019), Liu et al. (2019c), and Yousif et al. (2019).

4.3 Metamaterials

By designing and engineering conventional media, the innovative thermal metamaterial can create thermal properties that do not exist in nature, to build novel thermal devices. Lin et al. (2019) experimentally demonstrated a 12.5 cm^2, 90-nm-thick graphene metamaterial with approximately 85% absorptivity of unpolarized, visible, and near infrared light covering almost the entire solar spectrum (300–2500 nm), which makes it suitable for high-performance solar thermal applications. A graphene-based broadband solar absorber using Ag and Au structure was theoretically proposed and investigated in the spectral range from 100 THz to 1600 THz and the results showed an average absorption of 85.48% in infrared region, 97.51% in visible region, 89.57% in the ultraviolet region, and 92.72% absorption in the whole solar spectrum (Patel et al., 2019). A truncated Ti and Si cones metasurface was proposed for wide-band solar absorber application, which possesses an average absorption of 94.7% in the spectral region from 500 to 4000 nm (Liu et al., 2019d). A metasurface broadband solar absorber based on circular gold resonators was presented and analyzed in the spectral range from 155 THz to 1595 THz to study absorptance characteristics in infrared, visible, and ultraviolet regimes (Katrodiya et al., 2019), in which a maximum average absorptance of 89.79% and maximum absorptance peak of 99.90% at 1365 THz were demonstrated in one case study. Liang et al. (2019) proposed and demonstrated a broadband metamaterial perfect absorber consisting of monolayer Cr and Ti elliptical disks array located on the SiO_2–Au layer and the numerical results showed that the structure exhibits over 90% absorption in the spectral range from 382 to 1522 nm, and nearly perfect (> 99%) absorption in the spectral range from 564 to 1148 nm. An all-ceramic TiN/TiNO/ZrO_2/SiO_2 absorber with a high solar absorptance (92.2%) yet an ultralow thermal emittance (17.0% at 1000 K) was experimentally built (Li et al., 2019d), producing an unprecedented solar-thermal conversion efficiency (82.6% under 100 suns) which makes it attractive for high-temperature solar-thermal technologies.

5. PHASE-CHANGE HEAT TRANSFER, MATERIAL AND ENERGY STORAGE

With increasing energy demand in the development of technology and economic progress in the modern world, energy storage is important 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. Phase-change material (PCM) is one of the most appropriate and prospective materials for effective thermal energy storage from the 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. Recent development of the energy storage application with PCMs was comprehensively reviewed by Nazir et al. (2019).

However, the low thermal conductivity of PCMs limits its applications in the field of latent heat thermal energy storage (LHTES) system. In order to overcome this issue, various methods for thermal conductivity enhancement on PCMs were considered (Shabu and Dorca, 2019). Two major methods, encapsulation and nanomaterial additives, are most commonly employed to augment thermal conductivity (Drissi et al., 2019; Qiu et al., 2019a). Free convective flow and heat transfer of a suspension of nanoencapsulated PCMs in an enclosure was numerically investigated by Ghalambaz et al. (2019), achieving a relative enhancement of about 10% at a nondimensional fusion temperature of 0.25 compared to the base fluid. Song et al. (2019) demonstrated a novel microtubule encapsulated PCM for thermal energy storage prepared by embedding lauric acid (LA) in kapok fiber (KF) microtubules, and achieved an unprecedented high energy storage capacity up to 87.5% that of LA. To improve latent heat capacity and thermal conductivity of organic PCMs, a SiO_2/palmitic acid composite was prepared and experimentally studied; results showed an increase of 31.7% of latent heat capacity along with 12% in solid state and 7% in liquid state of thermal conductivity (Wang et al., 2019). Microencapsulation of the paraffin based PCM with 5% diamond-nanoparticles additive was also experimentally explored, leading to a 50% improvement in microcapsules thermal conductivity (Sadrameli et al., 2019). The microencapsulated PCM modified by graphene oxide (GO) and CNT hybrid filler were prepared via *in situ* polymerization and results indicated that the addition of GO and CNTs can largely enhance the thermal conductivity of the microcapsules, with 195% improvement at filler loading of 0.6 wt.% (Liu et al., 2019a).

Besides these two frequently used methods, Zhang et al. (2019a) experimentally synthesized paraffin-based PCMs incorporated with 3D porous diamond foam with volume fraction of only 1.3% and achieved high thermal conductivity and reliability. Yang et al. (2019b) experimentally evaluated that the inclination angle had a great influence on the formation and development of natural convection during melting of pure phase change material, affecting the solid–liquid interface propagation and heat transfer rate, as the full melting time was reduced by 12.28%, 22.81%, and 34.21% at 0^o, 30^o, and 60^o, respectively, compared with the case at 90^o. Tao et al. (2019) demonstrated that magnetically moving mesh-structured solar absorbers within a molten salt along the solar illumination path significantly accelerate solar-thermal energy storage rates by 107% while maintaining 100% storage capacity. Zhang et al. (2019c) analyzed and compared the metal melting performances in a cylinder enclosure with gallium as the PCM with different heating methods comprising external surface heating, internal surface heating, and uniform heat generation. Rauf and Saha (2019) embedded a metal matrix acting as a thermal conductivity enhancer for low thermal conductivity organic PCM in latent heat storage for solar applications.

6. HIGH-PERFORMANCE HEAT-EXCHANGE DEVICES

Enhanced heat transfer in high-performance heat exchangers, heat pipes, and rapid cooling techniques is of great practical significance.

6.1 Heat Exchangers

Tiwari et al. (2019) developed an additive manufacturing-enabled compact manifold microchannel heat exchanger and obtained shell-side heat transfer coefficient up to 45,000 $W \cdot m^{-2} \cdot K^{-1}$, which is an order of magnitude higher than that found in typical shell- and tube- and plate-type heat exchangers. Variyenli (2019) used a fly ash nanofluid as the working fluid in a plate heat exchanger to improve the heat transfer performance. The obtained experimental results showed that using the fly ash nanofluid enhanced the overall heat transfer coefficient between 6–20%. Khanlari et al. (2019) experimentally probed the effects of TiO_2/deionized water and kaolin/deionized water nanofluids as working fluids in the plate heat exchanger. The obtained results showed that a kaolin/deionized water nanofluid had higher thermal performance than TiO_2/deionized water nanofluid. Sözen et al. (2019) used TiO_2-deionized water as a working fluid to enhance the heat transfer rate in the plate heat exchanger. Thermosyphons have high effective thermal conductivity and are applicable in cooling devices and heat exchangers. Ramezanizadeh et al. (2019b) investigated the thermal performance of a thermosyphon by using Ni/glycerol–water nanofluid, and then designed a thermosyphon-based heat exchanger and compared its performance with a copper heat exchanger.

Nasirzadehroshenin et al. (2019) studied the impacts of Reynolds number, nanofluid volume fraction, twisted (pitch) ratio, and cavity diameter ratio on the exergy efficiency enhancement of a double-pipe heat exchanger. They found a strong correlation between the experimental and predicted values by machine learning ANN-Genetic Algorithm. Baghban et al. (2019) used ML approaches to predict the Nusselt number in a coil heat exchanger utilizing water–carbon nanofluid by considering Prandtl number, volumetric concentration, and helical number as the input variables. The used ML methods include a multilayer perceptron artificial neural network, adaptive neuro-fuzzy inference system, and least squares support vector machine (LSSVM). Results indicated that the LSSVM approach has the best performance and the proposed model by this approach has R-squared value equal to 1.

6.2 Rapid Cooling and Heat Pipes

The electronic devices in modern technology are experiencing a trend of exponential increase in power density, while the remaining space for heat dissipation is gradually reducing due to the necessity of electronic device for being lighter and thinner. The challenge of higher power and narrowing space in electronic devices have intrigued a large number of researches related to electronic cooling, achieved through various novel cooling strategies.

A closed-loop pulsating heat pipe (CLPHP) is a passive and promising device for the thermal management of modern electronic devices. Patel and Mehta (2019) proposed operational regime maps based on influencing parameters of a CLPHP. Hao et al. (2019) investigated the impacts of working fluid (deionized water, ethanol, and acetone, respectively), heat input, filling ratio on the startup performance, surface temperature oscillation, and thermal resistance of oscillating heat pipe (OHP) and showed that the acetone-filled OHP provides the best thermal performance. Ultrathin heat pipe was commonly utilized for solving the cooling problems of concentrated ultraslim portable electronic devices. An ultrathin flattened heat pipe with biporous spiral woven mesh wick was developed and the combined advantages of high permeability due to the large pores and large capillary force due to the small pores were elucidated (Zhou et al., 2019b). An aluminum flat plate heat pipe with dimensions of 120 × 120 × 2 mm fabricated by stamping method and micromilling method was proposed and a minimum thermal resistance value of $0.156^oC/W$ was achieved (Chen et al., 2019). A novel ultrathin aluminum flat heat pipe with thickness of

1.5 mm was developed to meet the increasingly urgent demand for compact and highly efficient thermal management solutions and results indicated that the structural parameters of the wicks have significant influence on the thermal performance of the heat pipe (Zhang et al., 2019b). A topology optimization approach was proposed to determine an optimal geometry of the wick structure sintered inside the flat heat pipe and the optimization of the shape of wick was shown to be able to increases the heat transfer capability, up to twice that of heat pipes with flat wicks of constant thickness (Lurie et al., 2019). An active air-cooling module based on a 1-mm-thick ultrathin miniature loop heat pipe with a flat evaporator for high-end ultra-slim laptop computers was presented and cooling energy with the proposed module was demonstrated to be reduced by 80% (Zhou et al., 2019a). Thermosyphon is a special type of heat pipe in which circulation of working fluid is assisted by gravity. Sardarabadi et al. (2019) explored an innovative two-phase closed thermosyphon filled with functionalized CNTs/water nanofluids as working fluid, which exhibited higher thermal efficiency and lower thermal resistance compared with the heat pipe filled with water.

Other efficient strategies for electronic cooling application include jet impingement, microchannel heat sink, thermoelectric cooing, oil immersion and hybrid method. A chip-level microjet liquid impingement cooler containing 4 × 4 nozzle arrays with 575-μm nozzle diameter is manufactured using the stereolithography 3D printing technology and the results from experimental characterization show a low thermal resistance of 0.16 $cm^2 \cdot K/W$ at a flow rate of 1000 mL/min and a pressure drop of 0.3 bar with good temperature uniformity (Wei et al., 2019). A novel permeable membrane microchannel (PMM) heat sink geometry is proposed and fabricated using direct metal laser sintering (DMLS) of an aluminum alloy and both lower thermal resistance (17% reduction) and pressure drop (28% reduction) are found at a constant pumping power of 0.018 W as compared with manifold microchannel heat sink (Collins et al., 2019). Tiwari and Moharana (2019) improved design of raccoon microchannel heat sink with a combined change in wave amplitude and wavelength along the channel length. The nano-PCM made by mixing multiwall carbon nanotubes (MWCNTs) with paraffin was tested for heat sink application and faster cooling performance under free convection condition was demonstrated as compared with normal PCM (Farzanehnia et al., 2019). A 3D numerical modeling of conjugated heat transfer was performed for laminar flow of microencapsulated PCM slurry in microchannels, revealing that the addition of PCM capsules in pure water resulted in enhanced heat transfer performance of the heat sink (Shaukat et al., 2019). Wiriyasrt et al. (2019) scoped out the cooling enhancement of a dual processor computer using thermoelectric air cooler module. An experimental investigation demonstrated that the potential of oil immersion cooling to be utilized as a new and more effective cooling strategy for thyristor-based switches, with a reduction of thermal resistance of 30 times compared with air natural convection (Pires et al., 2019).

7. CONCLUSIONS

From the selected literature published in 2019 archival English journals, it is indicated that significant attempts were made to research and develop heat transfer augmentation. As modern devices and components are shrinking in physical size while continuing to add functions, the power densities generated or dissipated are increasing. Thus, it has become crucial to explore new methods for enhancing heat transfer. In particular, more attention is being directed toward understanding the underlying mechanisms from micro/nanoscopic views or even at atomic levels. For example, interfaces between dissimilar materials with perfect contact in the nanoscale can impede heat transfer. Interfacial thermal resistance, which differs from contact resistance, is one of the critical challenges for enhancing thermal transport to the required extremely high power densities. Diamond is currently used to remove large heat flux from high-end equipment and devices. Unfortunately, diamond in nature is rare and expensive, and synthetic quality diamond is difficult and costly to produce. Research with other high-conductivity materials such as CNTs and graphene is being actively pursued. Search for new materials and/or devices with ultrahigh thermal conductivity or ultrahigh thermal energy storage capability continues to be active. In the meantime, enhancement of phase-change heat transfer has also attracted increasing attention because it involves high heat flux and is of great practice in heat pipes and heat exchangers. Phase-change material is one of the most appropriate and prospective materials for effective thermal energy storage and has gained a wide range of applications in various fields, such as buildings, solar energy, and power systems. Various methods for enhancing the low thermal conductivity of PCMs have been attempted; among which, encapsulation and nanomaterial additives are commonly adopted. Near-field phenomena existed in nanoscale photon and phonon transport are being exploited for enhancing heat transfer at the nanoscale. Enhancement of near-field radiation coupling with surface plasmon and phonon polaritons is also being investigated. Increasing solar radiation absorption improves the efficacy of solar energy utilization. Thermal metamaterial can be manipulated to the direction of thermal transport and the efforts create thermal properties that do not exist in nature. Traditional issues lingering with the passive or active techniques for convective heat transfer enhancement call for more experimental investigations and applications in thermo-fluid and energy systems and other engineering practice. A strong emphasis has been placed on compound techniques which combines a few passive and/or active techniques. Machine learning is utilized in the studies of enhanced heat transfer. For example, nanofluids have very complicated thermophysical properties and nonlinear characteristics. Machine learning can advance nanofluid heat transfer enhancement research because of its capability to handle a large number of complex and interrelated data.

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