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Thermal Energy, Process and Transport Intensification - A Brief Review of Literature in 2021 and Prospects

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Abstract

This review provides a brief literature survey recorded by the Web of Science (WoS) in 2021 on the studies of heat transfer enhancement (HTE), thermal energy, process and transport intensification technologies. A topic search containing "heat transfer" or "heat transport" or "thermal transport" in the WoS resulted in over 31,360 papers published in 2021 and more than 30% were relevant to HTE, thermal energy, process and transport intensification, which indicates the importance and rapid development of these technologies and their applications. The chosen

studies focus on HTE, thermal energy, process and transport intensification, which are grouped into heat conduction enhancement, convection HTE, boiling and condensation HTE, radiation HTE, thermal energy and process intensification and cross disciplinary research involving two or more techniques. Heat conduction enhancement research covers the research topics on thermal conductivity augmentation using various methods for thermal interface materials, phase change materials (PCMs), composite materials with nano additives, nano coatings, nanofluids, finned metal foam and fins in heat exchangers. Convection HTE research includes passive, active and compound techniques, and their engineering applications. Boiling and condensation HTE research is critical in the development of advanced and cutting-edge thermal energy and process intensification technologies. Radiation HTE research focuses on near-field radiation and thermophotovoltaic. Thermal energy and process intensification research involves thermal and power systems, energy conversion, energy storage, thermal processes, renewable energy, and thermal management of electronics and high-end equipment and cross disciplinary topics. The prospects of thermal energy, process and transport intensification technologies are given according to this literature review. Studies of thermal energy, process and transport intensification techniques are immense, encompassing every aspect from understanding the experimental results, observed phenomena, fundamental theory and physical mechanisms of various intensification techniques to their practical engineering applications. Engineering design, experimental and numerical studies of emerging intensification techniques using new interfacial materials, nanofluids, micro- and nano-structures and microchannels and combination of two or more methods etc. have been conducted. Compound enhancement techniques incorporating conventional and innovative techniques and their applications in energy recovery, energy conversion, energy storage, renewable energy, combined heat, cooling and power generation technologies, hydrogen

production and energy system, thermal management etc. play a crucial role in achieving zero carbon target by 2050 and provide opportunities for research and development of innovative intensification technologies.

Keywords: Heat transfer, Enhancement, Boiling, Condensation, Nanoscale, Materials, Interface, PCM, Thermal management, Heat exchanger, Device, Process, Transport, Thermal energy, Intensification, Energy recovery, Energy conversion, Energy storage.

1. Introduction

HTE or augmentation or intensification means the improvement of thermal performance of any heat transfer and mass process, heat exchanging medium, thermal component, heat transfer device, heating/cooling equipment, thermal energy technologies, thermodynamic system. Following the reviews conducted on HTE, thermal energy and process intensification literature in 2019 and 2020 (Guo et al., 2020; Guo et al., 2021), the present review continues to circumscribe HTE, thermal energy, process and transport intensification papers published in archival journals in English language in the single year 2021. Consideration has been given to the research regarding HTE, thermal energy and process intensification and the publication amount is huge, thus, selection is unavoidable. Nonetheless, the authors tried to cover a wide range of areas related to the relevant intensification techniques, namely active, passive and compound techniques in heat conduction, PCMs and interfacial and composite materials conduction, nano coatings, convective heat transfer, nanofluids, boiling and condensation heat transfer, structured surfaces, microchannels, radiation heat transfer, near-field radiation and thermophotovoltaic, thermal energy and processes, thermal energy storage, high heat flux cooling, thermal management, process heat transfer, and high-performance heat-exchange elements and devices, etc.

Table 1. Yearly number of papers on heat transfer and HTE indexed in the WoS from year 2011 to 2021.

Year	HT*	HT yearly increase (%)	HTE**	HTE yearly increase (%)	HTE/HT (%)
2011	14800	6.49	2471	12.21	16.69
2012	16910	14.26	3070	24.24	18.15
2013	16737	-1.02	3135	2.02	18.73
2014	19508	16.56	3828	22.11	19.62
2015	19989	2.47	4055	5.93	20.29
2016	22684	13.48	5061	24.81	22.31
2017	25442	12.16	5928	17.13	23.30
2018	25713	1.06	6382	7.66	24.82
2019	29158	13.40	7647	19.82	26.22
2020	29913	2.59	8700	13.77	29.08
2021	31360	4.84	9487	9.05	30.25

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

**HTE search results further containing keywords either “enhancement” or “augmentation” or “intensification” or “enhanced” or “augmented” or “intensified” or “intensification” inclusive of HTE, thermal energy, process and transport intensification.

A topic search in the database of WoS with keywords “heat transfer” or “heat transport” or “thermal transport” conducted on May 22, 2022 returned 31,360 papers published in 2021, which symbolizes a 4.84% yearly increase compared to 2020. A further search refinement containing words “enhancement”, or “augmentation”, or “intensification”, or “enhanced”, or “augmented”, or “intensified”, or “intensification” resulted in 9,487 papers relevant to HTE, thermal energy and process intensification published in 2021, which is 30.25% of the overall heat transfer publications. This ratio keeps increasing. Table 1 lists the yearly paper number data in heat transfer and HTE, thermal energy, process and transport intensification, respectively, acquired from such topic searches for the period from 2011 to 2021. It is worth mentioning that the data listed in the table may be slightly different from the data surveyed last year (Guo et al., 2021) because the WoS updates dynamically its database. It is observed that the enhancement and intensification-related paper ratio is steadily increasing from a bit over 10% in 2001 (Guo et al., 2021) to cross the line of 20% in 2015 and goes over 30% in 2021. This indicates that the demand of research on thermal energy, process and transport intensification has been continuously increasing. Certainly, HTE, thermal energy, process and transport intensification are important in the research and development of the intensification techniques in many areas such as high performance heat exchangers, thermal management of data centers, electronics cooling, thermal energy storage, heat, cooling and power cogeneration, hydrogen production and storage, hydrogen energy systems, advanced manufacture, advanced materials, building environment, transportation, aerospace, defense technologies, materials, chemical and bio-engineering, nano and micro technologies, renewable energy, carbon capture storage and unitization and zero carbon technologies etc.

2. Heat Conduction Enhancement

This section presents a brief literature survey on the selected studies of the augmentation of thermal conductivity and heat conduction using various methods for thermal interface materials, PCMs, composite materials with nano additives, nano coatings, nanofluids, finned metal foam, and fins in heat exchangers, etc.

Ma et al. (2021c) reviewed recent progresses on effective methods to enhancing thermal conductivity of materials using filler functionalization and processing, filler hybridization and coating, filler orientation and network of thermal interface materials. Cheng et al. (2021a) reviewed the recent studies of enhanced thermal conductivity of PCMs based on zero-dimensional (0D), one-dimensional (1D), two-dimensional (2D), and three-dimensional (3D) nanoadditives together with hybrid nanoadditives. They addressed the research on structured additives to PCMs to enhance the effective thermal conductivity and thermal transport. Kant et al. (2021) reviewed the existing techniques to enhancing the thermophysical properties of PCMs inclusive of thermal conductivity. Zhang et al. (2021e) reviewed the research regarding in personal thermal management using thermally conductive composites along with the mechanistic models and engineering strategies for conduction HTE. Pavía et al. (2021) reviewed research on thermal conductivity in term of the performance regarding the amount of graphene used for making nanofluids.

Singh et al. (2021) investigated the heat conduction enhancement of a binary eutectic PCM laden with different concentrations of COOH-functionalized graphene nanoplatelets for a multi-effect solar cooling thermal storage system. Yu et al. (2021) studied the formulation, fabrication and characterization of a novel composite used for high-temperature heat energy storage. Their proposed composite is a shape-stable PCM consisting of eutectic chloride ($MgCl_2$–NaCl–KCl), expanded graphite (EG) for conduction HTE and shape stability, and SiO_2 nanoparticles for the further improvement of the specific heat and thermal conductivity of the composite. Chen et al. (2021d) designed a novel polyethylene glycol (PEG) PCM composites supported by $Ti_3C_2T_x$@polyvinyl alcohol foam skeleton, which have the advantages like low-cost, scalable and simple preparation method by freeze-drying after PEG introduced into the skeleton via vacuum impregnation. The thermal conductivity of $Ti_3C_2T_x$/PEG composite containing 7.68 wt.% skeleton was 4.2 times higher than the PEG. Desai et al. (2021) investigated the PCM based thermal control unit for controlling the peak temperature of an electronic device and also used novel metallic fins to enhance the heat conduction. Larwa et al. (2021) studied a hydronic radiant floor heating system integrated with a macroencapsulated PCM. The high heat conduction in mortar greatly increases the overall performance of the PCM integrated underfloor heating system. Arshad et al. (2021) numerically studied a hybrid nanocomposite PCM filled heat sink for cooling of electronic devices. They added graphene oxide (GO) and silver hybrid nanoparticles into the RT-28HC to enhance heat conduction. Wang et al. (2021a) studied the heat conduction enhancement of paraffin mixed with nanoparticles of Al_2O_3, CuO, and multi-walled carbon nanotube (MWCNT), which is used for cooling multiple heat sources.

Studies on enhancing the thermal conductivities of interface materials have been extensively investigated. Huang and Guo (2021) studied the effect of epilayer structure and thickness on reducing thermal interfacial resistance (TIR) and enhancing heat conduction in heterostructures and found the existence of optimal epilayer thickness and structure. Ahmed and Bhargav (2021) investigated nanolayer heat transfer at the solid-fluid interface to determine its role on the enhancement of thermal conductivity of Al_2O_3-CO_2 nanofluid for supercritical and gaseous phases. Wang (2021) found that the graphene with covalent grafts or noncovalent molecular interposers could lower the thermal boundary resistance at the interface between epoxy and graphene. Xu et al. (2021c) experimentally studied the geometric phase in a macroscopic thermal convection-conduction system and two moving rings with equal-but-opposite velocities, joined together by a stationary intermediate layer.

Polymer composites are widely used in many areas such as microelectronics and wireless communication, and their high thermal conductivity and low dielectric loss are highly pursued for efficient heat dissipation and signal transmission. Li et al. (2021d) studied ultrahigh through-plane thermal conductive epoxy composites with carbon fiber networks by in-situ solidification within an epoxy and found that the thermal conductivity of these epoxy composites was about 171 times that of the pure epoxy. Xie et al. (2021) improved the thermal conductivity of a low-loading

(5.5 vol.%) polypropylene nanocomposite film with uniform-dispersed and interfacial engineered boron nitride nanosheets via one-step alkyl modification. Lin et al (2021a) studied 3D graphene-based aerogels having an anisotropic open-cell and well-oriented structure for enhancing the thermal conductivity of polydimethylsiloxane (PDMS). The nanocomposites show anisotropic thermal conductivity. Jiang et al. (2021b) studied advanced thermoresponsive polymeric composites containing a 3D interconnected boron nitride (BN) network to improve the thermal conductivity, heat transfer behavior, shape memory and mechanical properties.

The advanced nanocoating technology paves the way to enhance heat transfer. Liang et al. (2021) experimentally investigated the thermal conductivities of epoxy/BN@SiO_2 composites and found that increasing the coating thickness or filler content would decrease the enhancement of heat conduction. Pezzana et al. (2021) studied forming 3D structures with enhanced thermal conductivity by vat printing a silicone–acrylate based nanocomposite and used BN nanoparticles to enhance the thermal conductivity of a PDMS-like photocurable matrix. Zhu et al. (2021b) studied thermally conductive geopolymer (GP) nanocomposites by incorporating silica-coated multi-walled carbon nanotubes (SiO_2-CNT) into the GP matrix. The SiO_2 layer not only improved the dispersion of CNT, but also alleviated the modulus mismatch between CNT and GP. Zhang and Guo (2021) formulated thickness dependence and anisotropy of the thermal conductivity in thin-film diamond used as a heat spreader to reinforce hotspot cooling in high-power electronics.

Senthilkumar et al. (2021) experimentally investigated an aluminum pin-fin heat sink for enhanced heat transfer by using three different materials (Cu, Ag, Al)-based nanocoating with high thermal conductivities. They compared the surface characteristics of the coated samples with the uncoated sample and evaluated the performance of the heat sink with and without coating under forced convection conditions. Yuan et al. (2021) proposed a novel heat exchanger efficiency approach based on various industrial heat exchanger designs and studied the performance of three types of heat exchangers with anticorrosion coating. They presented the thermal and exergetic performances of heat exchangers changes with the thermal conductivity of anticorrosion coating when the heat fluids are gas-gas, gas-liquid, and liquid-liquid, respectively.

Nanofluids are potential heat transfer fluids in many engineering applications. Compared to metal, metal oxide nanoparticles and carbon nanotubes, graphene with its extremely high intrinsic thermal conductivity has been considered one of the best candidates to prepare nanofluids. Li et al. (2021i) experimentally studied the enhanced performance of heat transfer and thermophysical properties of ethylene glycol-based silicon carbide-MWCNT hybrid nanofluids as coolant in automobile engine cooling system. Hashimoto et al. (2021) found that the inelastic X-ray scattering for the nanofluid composed of SiO_2 nanoparticles and ethylene glycol (EG) aqueous solution revealed one of the mechanisms for the thermal conductivity enhancement of nanofluids. The high-frequency sound velocity derived from the inelastic X-ray scattering spectra of nanofluids may be correlated with the structural relaxation of solvent molecules and corresponding thermal conductivity. Öcal et al. (2021) experimentally investigated the enhanced thermal conductivity of TiO_2-$CaCO_3$/water hybrid nanofluids at five different concentrations.

Hajabdollahi et al. (2021) studied the thermoeconomic aspects of gasket-plate heat exchangers by using the boehmite alumina nanoparticles with four different nanoparticle shapes including platelet, brick, cylinder, and blade. Qu et al. (2021) employed an amino-functionalized black phosphorene (BP) fabricated by ball milling to react with carboxylated multi-wall carbon nanotubes via covalent bonds and prepared a new nanofiller (BP–MWCNTs) with high thermal conductivity and excellent flame retardancy. Huang et al. (2021b) experimentally investigated the thermal performance of finned metal foam heat sinks with a PCM. Their results indicate that the

HTE with addition of metal foam exceeds the heat transfer loss due to the suppression of natural convection. Safari et al. (2021) experimentally and numerically investigated the effects of straight and bifurcated fin configurations on the melting behavior of paraffin inside the shell-and-tube heat exchangers. They considered three different fin arrangements: (a) cross arrangement, (b) diagonal cross arrangement, and (c) arranged evenly at the lower half of the heat exchanger. Bedi and Subbarao (2021) experimentally and numerically studied the phenomenon of backward conduction through microchannel heat sinks and compared the experimental results to the results of numerical simulation.

3. Convection HTE

Convective HTE methods are categorized into passive, active and compound techniques such as solid surface modification, additional device, inserts, additives, functional fluids, external actions and combined two or more techniques. Experimental studies, numerical simulations and analytic studies of the convection HTE mechanisms are extensively performed to understand the enhanced heat transfer processes and phenomena and develop relevant technologies. High-performance heat devices and exchangers with convection HTE techniques are widely used in engineering applications including thermal energy, renewable energy, energy storage, refrigeration, air conditioning and heat pump systems, nuclear engineering, hydrogen production and energy system, chemical processes, aerospace, electronics and microelectronics, and cooling of gas turbine and internal combustion engine, materials production, mechanical and manufacture engineering, thermal management and so on. Mousa et al. (2021) reviewed single-phase HTE techniques and made a thorough comparison by analyzing the heat transfer rate, pressure drop, and other operational aspects. They summarized the key learning data for design optimization enabled by additive manufacturing and machine learning algorithms, which helps to inform the next-generation heat exchanger design methodologies for many practical applications such as electrification of vehicles, computing, and classical industries.

3.1. Passive techniques for convection HTE

Using fins is one of the conventional techniques to enhance convection heat transfer. Soltani et al. (2021) investigated the combined effects of both fins and rotation on the latent heat thermal energy storage (LHTES). Li et al. (2021a) proposed several 3D perforated-fin models to enhance the heat storage performance and studied the perforated fin structure by varying the hole diameter and hole location. Sadeghianjahromi et al. (2021) proposed novel designs of fins that can surpass the most widely used louver fin geometry for air-cooling applications and numerically studied several innovative fin types such as ring fins, circular disk fins, and hexagonal disk fins compared with a louver fin-and-flat tube heat exchanger in terms of thermal resistance at the same pumping power. Vu and Dhir (2021) studied the air-side heat transfer and pressure-drop in heat exchangers with various modifications to heat transfer surfaces. Five different heat exchanger configurations, namely, a bare tube and tubes with a plain fin, spherical dimple fin, conical dimple fin, and wavy fin were used in their study. Hu and Yeh (2021) theoretically investigated 2D heat transfer characteristics of heat sink modules made of various metal materials including Cu, Al, Al alloy, Mg, Zn, Fe, constantan, and stainless steel for the light-emitting diode equipment in forced convection. Bhandari and Prajapati (2021) numerically investigated micro-pin fin heat sinks with novel arrangements of the fins by varying the fin height in an array of two, three, and four fins used in stepped-type pin fin heat sink. Zhu et al. (2021a) studied the fin effects of corrugated membranes to support the membrane channels in the core of a membrane-type total heat exchanger, which could minimize the building energy consumption associated with forced ventilation by recovering both heat and moisture from ventilation air. Du et al. (2021) optimized a rectangular duct with pin fins and dimples/protrusions by using four different optimal objectives: entropy generation, entransy dissipation, energy, and volume goodness factor. Kim (2021a) investigated the air-side heat transfer performance of fin-and-tube heat exchangers with different fin patterns and tube geometry under wet conditions. The fin configuration consisted of the herringbone and sinusoidal fins and the tube geometry included the round and oval tubes. Moon et al. (2021) investigated the HTE behaviors of single-phase forced convection inside additively manufactured internally finned channels and developed a genetic algorithm to optimize the fin geometry to minimize total thermal resistance for laminar flow or convection thermal resistance for turbulent flow.

Zhao et al. (2021c) proposed a novel method to enhancing the heat transfer performance on the internal tip surface of gas turbine blades and analyzed the effects of delta-winglet vortex generators (DWVGs) and their angle of attack on the vortical structures and the mechanisms of the HTE. Kumar et al (2021) investigated the heat transfer and fluid flow characteristics of a heat exchanger with a twisted tape having multiple V-cuts with circular and elliptical perforations inserted the heat exchange tubes and analyzed the effects of tape geometries on the Nusselt number in conjunction with friction factor for different types of inserts. Dang and Wang (2021) investigated the convective HTE mechanisms in a tube with a new kind of twined coil insert. Çolak (2021) investigated the effect of the algorithms used in the training of artificial neural network on prediction of the specific heat of ZrO_2/water nanofluid. Wang et al. (2021c) investigated the heat transfer performance of multi-tube heat exchangers with transverse corrugated tubes and helically corrugated tubes and analyzed the complex flow features coupled by multiple secondary flow, spiral flow and turbulent pulsation and the HTE mechanisms by coupling the global flow contours and entropy generation distributions. Tepe (2021) investigated the effect of punched triangular ramp vortex generator on the heat transfer characteristics of a fin-tube heat exchanger. Alklaibi et al. (2021) investigated the heat transfer characteristics of a hybrid nanofluid of Nanodiamond + Fe_3O_4/water with concentrations of 0.05%, 0.1%, and 0.2% at the Reynolds number from 2000 to 22,000. Zheng et al. (2021a) investigated the alternation of clockwise and counterclockwise twisted tape (AT tape), and the AT tape in conjunction with three types of edge notches (*V*-cut, semicircle-cut, and rectangular-cut) on the heat transfer and flow friction characteristics in a circular copper tube at uniform heat flux in the laminar flow regime using water as working fluid.

Ma et al. (2021d) designed a novel channel with a partition between the leading and trailing side to enhance the heat transfer in both sides due to the Coriolis force and employed a 3D numerical model with realizable k-ε turbulent model to characterize the flow and heat transfer in the novel channel. Rahimi et al. (2021) investigated a novel heat exchanger consisted of a spiral plate shell and a set of multipass tubes crossed through the shell channels with U-junctions and evaluated its performance using experimental and numerical methods. Zhao et al. (2021a) employed a fluid structure interaction model and a 2D unit model to investigate the vibration and heat transfer of a double-helix tube bundle in the sensible heat storage process of ternary nitrate under different pulsating parameters. Chauhan et al. (2021) studied the impact of thermal aging on a dielectric fluid for single-phase immersion cooling on the low-loss material printed circuit board's (PCB's) thermomechanical properties. Baysal and Bademci (2021) investigated the heat transfer of a plate-type turbulator placed in a circular tube and analyzed the effects of the obtained temperature contours and velocity vectors on the flow characteristics of the turbulator in the heat exchanger. Parlak et al. (2021) optimized the sinusoidal wavy structure of a channel cooler for active cooling to obtain the best heat transfer performance by combining the experimentally validated conjugate CFD method with the response surface methodology. Cruz et al. (2021) studied the internal flow and heat transfer in corrugated tubes of different helical pitch in both the laminar and turbulent regimes in order to characterize the 3D flow and the influence of corrugation geometry on pressure drop and convective heat transfer. Dagdevir and Ozceyhan (2021) investigated the effects of different twisted tapes on the thermal performance of a heat exchanger using EG and water mixtures. Boules et al. (2021) investigated the flow and heat transfer across a horizontal cylinder in crossflow wrapped with whole and segmented layers of metal foams and measured high porosity and thermal conductivity metal foam layers with two different thicknesses.

Narankhishig et al. (2021) reviewed the experimental and numerical studies on the convection HTE of various nanofluids, particularly hybrid nanofluids including some applications in thermal systems. Prasad et al. (2021) experimentally studied the heat transfer, friction factor, thermal performance, and effectiveness of Cu/water nanofluids flow in a double-pipe U-bend heat exchanger. Tao et al. (2021) experimentally investigated the heat transfer of a radiator in a proton exchange membrane fuel cull cooling system with BN nanoparticles mixed with 50/50 water and EG as the coolant. Çiftçi et al. (2021) used aluminate-based spinels of Fe, Mg, and Zn elements with the binary combinations of Fe:Mg, Fe:Zn, and Zn:Mg and prepared aqueous hybrid nanofluids with a combination ratio of 50:50. The nanofluids were used in the heat pipes of the air-to-air heat exchanger and the efficiency and thermal resistance of the heat pipes were investigated in both hot and cold air passages at a wide range of Reynolds numbers. Acir et al. (2021) analyzed the thermal performance of the VVER-1000 reactor with thorium fuel and coolant containing Al_2O_3, CuO, and TiO_2 nanoparticles. Their results show that adding nanoparticles to the coolant and using thorium as an additive to fuel the rise of coolant temperature can be augmented as compared to traditional combination of fuel and water while reactor remained within safety limits. Mukherjee et al. (2021) studied the thermal performance, pumping power, efficiency, exergy loss and feasibility of TiO_2/water nanofluid flowing inside a circular tube at mass concentrations from 0.01 to 1%.

Dong et al. (2021) investigated a solar air heater with novel inclined groove ripple surfaces and analyzed the effect of groove amplitude, attack angle, and array number on the overall heat transfer and fluid flow performance of the air heater. Lei et al. (2021) studied the HTE behaviors of water, paraffin, and copper foam as heat transfer fluid, PCM, and heat transfer enhancer, respectively. Işık and Tuğan (2021) performed 3D molecular dynamics simulations to design and analyze a single-shell- and double-tube-pass at steady-state flow. Ünverdi et al. (2021) investigated the thermal and hydrodynamic performance in the tube side of a minichannel shell-and-tube heat exchanger while its shell side was kept under optimal conditions. Özbaş (2021) conducted research on the HTE in a diffusion absorption refrigeration system using suspension of FeO/TiO_2 nanoparticles in ammonia/water base-fluid as a working solution. Chen et al. (2021e) investigated the horizontal capillary filling characteristics of FC-72 refrigerant in silicon-based microchannels with small aspect ratio. Ye et al. (2021) studied the effects of different kinds of coolants on the fluid flow and heat transfer in a pin-finned internal channel and proposed a new pin-fin structure detached from one endwall with a round-tip to enhance the heat transfer.

3.2. Active techniques for convection HTE

Chitsazan et al. (2021) reviewed studies regarding multiple impinging round jet systems and focused on the factors occurring in the drying of sheets and influencing the heat and mass transfer rate. Kansy et al. (2021) studied the spray cooling under automobile boundary conditions. Ismail et al. (2021) investigated the effects of two synthetic jet orientations on the Nusselt number of combined convection heat transfer by using two synthetic jet orientations−horizontal and vertical at eight different Reynolds numbers. Allauddin et al. (2021) carried out Reynolds-averaged Navier-Stokes (RANS)-based numerical investigation to compare the performance of the multiple jets impingement system with air, water, and alumina oxide-water nanofluid and compared the characteristics of jets impingement on the target plate with and without pin-fins under crossflow conditions. Wang and Zhang (2021) numerically investigated the mechanism of the holistic optimization for airflow and heat transfer as well as the arrangement of axial fans in a cold room. They adopted field synergy principle to obtain the theoretically optimal airflow organization for enhancing convective heat transfer based on the solution of governing equations derived by the variational method. Gao et al. (2021b) studied the role of the chevron-nozzle on the jet impingement onto a specifically confined conical-concave target and considered both the convective heat transfer and the discharger coefficient of the nozzle in the jet impingement configuration. Pal et al. (2021) investigated the transport enhancement of impinging annular jets and discussed the possibility of HTE on an impinging surface under annular nozzle using angled exit jet. She et al. (2021) studied the spray zone characteristics of two types of full cone nozzles by setting up a liquid-nitrogen-spray-cooling experimental platform and analyzed the relationships between the heat flux and the superheat, the heat transfer coefficient and the superheat, and the heat flux and the heat transfer coefficient by controlling the liquid nitrogen flow, orifice of nozzle and heat sink area.

The magnetohydrodynamics (MHD) technique is widely used in various industrial fields such as manufacturing of semi-conducting wafers, the blanket flows of fusion reactors, and the continuous casting process. For the improvement of internal and external casting defects, Lee and

Park (2021) devised various flow braking systems using the MHD technology and applied them to actual continuous casting plants. They also numerically investigated the hydrodynamic characteristics in the continuous casting mold (CCM) when a uniform magnetic field flux was applied to the CCM externally. Tiwari and Yeom (2021) studied the air channel flow using a piezoelectric fan and obtained significant improvements in channel convection heat transfer. Poncet et al. (2021) investigated the HTE performance of forced convection with sonication of dual-frequency ultrasound. Wang et al. (2021d) studied parametric optimization of an interrupted microchannel heat sink with rectangular ribs and compared interrupted microchannel heat sinks with different kinds of rectangular ribs having different width, length, and locations with a straight microchannel and microchannel interrupted chamber.

3.3. Compound techniques for convection HTE

Rai and Hegde (2021) studied the conjoint effect of circular fin turbulators and Al_2O_3 nanofluid on the heat transfer and fluid flow characteristics in a helically wound coil-in-shell heat exchanger used for waste heat recovery and developed the correlations of the Nusselt number, friction factor, and thermal-hydraulic performance in the laminar and turbulent regimes, which favorably agree to acceptable limits. Gelis and Akyureck (2021) adopted two passive HTE methods: double pipe mini heat exchanger and hybrid nanofluids to enhance the heat transfer performance of the heat exchanger. Sundar et al. (2021a) experimentally studied the friction factor and thermal performance factor of high-Prandtl number vacuum pump oil-based magnetic Fe_3O_4 nanofluids flow in a tube with various core-rod inserted wire coil inserts. Naveed et al. (2021) analyzed the mechanism of heat transfer and flow of hybrid nanofluid over a curved stretchable surface by integrating the Joule heating effects and including the melting state of heat transfer. Farahani et al.

(2021b) investigated the effects of fins, magnetic fields, and nanoparticles on the melting of PCM in a finned cavity and evaluated the effects of fin and its shape, porous fin, adding nanoparticles, the non-uniform magnetic field, and the oscillating magnetic field. Koca (2021) investigated the effect of Al_2O_3/water-based nanofluids on HTE performance in heat exchangers with rotating straight inner tube and compared their experimental data of nanofluid to those of pure water. Sundar et al. (2021b) investigated the heat transfer of reduced graphene-oxide/cobalt-oxide/water hybrid nanofluid in a tube with coiled wire inserts.

Kummitha et al. (2021) studied the structure of vortices induced by the spiral coil insert in a parallel plate channel and analyzed the effects of vortices on velocity and temperature fields using a nanofluid. They recorded a better heat transfer rate due to the combined effect of spiral coil vortices (swirl flows) and nanofluid's desirable fluid properties. Pazarlioğlu et al. (2021) investigated the effect of impinging jet cooling on a solar air heater with and without longitudinal fins and analyzed the effect of fin height and mass flow rate of working fluid on the thermal efficiency of the solar air heater. Farahani et al. (2021a) studied the effect of a nonuniform magnetic field on the melting process of lauric acid PCM in a finned triple tube. The effects of fin length, the radius of the middle tube, porous fin, nanoparticles, and nonuniform magnetic field were investigated. Zainith and Mishra (2021) investigated the friction factor and thermal performance factor of a coil side for a helical coil heat exchanger by using non-Newtonian nanofluids for various modified Dean numbers ranging from 10 to 300 with three different curvature ratios δ equal to 0.072, 0.083, and 0.098. Ma et al. (2021a) studied the electro-thermo convection of a perfectly insulted liquid induced by two energized and heated circular cylinders in a cold square cavity and applied a newly developed unified lattice Boltzmann model for direct simulation of flow field, electric potential, charge density and temperature field. Zhang and Zhang

(2021) investigated the heat transfer and pressure drop performance of magnetic nanofluids, and revealed that the effect of alternating magnetic field on local heat transfer coefficient was better than that of unidirectional and non-magnetic fields along flow direction.

4. Boiling and Condensation HTE

Boiling and condensation processes play an important role in various thermal energy systems, energy storage and saving, and industrial processes, etc. Various HTE techniques may be applied to boiling and condensation to attain three apparent desires: reducing wall superheat temperature, enhancing pool boiling heat transfer coefficient, and improving critical heat flux (CHF). New emerging research on boiling and condensation HTE using micro- and nanotechnology becomes popular, 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, ribbed tubes, inserts, applying electric and magnetic fields are continuously investigated to achieve advanced knowledge, physical mechanisms, prediction methods and engineering applications to improve thermal energy and processes efficiency, develop innovative technologies and reduce carbon emissions.

4.1. Pool Boiling HTE

Singh and Sharma (2021) reviewed various surface modification methods such as nanomaterial coating, nano/micro porous coating, nano/micro structured surface for pool boiling and flow boiling HTE. Kim (2021b) experimentally investigated the pool boiling characteristics using lithium bromide solutions in seven low-fin tubes having a fin height range of 1.1-1.8 mm and fin pitch range of 0.64-1.34 mm. Sajjad et al. (2021) investigated compound surfaces having multi-dimensional enhancement mechanism (earlier boiling initiation, efficient and extended limit of heat transfer) by incorporating microgrooves into the rough sandblasted surfaces. Li et al. (2021h) designed a novel pillar-structured surface for nucleate boiling HTE, namely a pillar-structured surface with distributed wettability-modified regions on the top of each pillar and used a 3D thermal multiphase lattice Boltzmann model with liquid–vapor phase change to simulate the boiling heat transfer on the pillar-structured surface with distributed wettability-modified regions and the associated mechanism of nucleate boiling heat transfer enhancement.

Min and Guo (2021) conducted a molecular dynamics simulation to investigate pool boiling of water on the copper substrate coated with five types of stable defective graphene monolayer. Their results show that most of the cases coated with defective graphene have higher initial heat flux and reach equilibrium faster than the pristine graphene‒coated case under the isothermal heating condition. In particular, all the graphene coatings enhance the CHF value for pool boiling by nearly two orders of magnitude. Lim and Hung (2021) demonstrated that the ultrafast transport of water molecules through the nanostructures of graphene-nanoplatelets forms an ultrathin film of water that prompts effective absorption of latent heat of vaporization. Jiang et al. (2021c) studied pool boiling of deionized water on the surface of cylindrical pillar arrays of different sizes and the ordinary smooth surface under atmospheric pressure. Çiftçi (2021) numerically investigated the saturated pool boiling heat transfer of two different aqueous nanofluid suspensions, namely, kaolin-distilled water and bauxite-distilled water using CFD approach and time-dependent volume-of-fluid (VOF) multiphase model to specify the vapor volume fractions and velocity vectors in both distilled water and the prepared nanofluid suspensions. Hoke et al. (2021) investigated pool boiling of R134a in high aspect ratio silicon microchannels and postulated that the area enhancement reduced heat transfer coefficients and the performance increase was caused by increasing the number of active nucleation sites. Ma et al. (2021e) studied pool boiling on multi-layer gradient aperture open-cell porous copper, obtained the pool boiling curves, and analyzed the corresponding bubble dynamics of these porous copper samples. Li et al. (2021e) investigated a porous surface covered by microcavities fabricated using the three-step method of a powder sintering technique followed by chemical modification methods and systematically studied the pool boiling heat transfer and the bubble dynamics. Jo et al. (2021) used electroplated Ni nanocones with a hierarchical structure to enhance pool boiling on a surface and derived the CHF and effective heat-transfer coefficients. Zheng et al. (2021b) investigated a new jet impingement cooling method by applying nucleate boiling the porous surface with a microcolumn array and investigated the HTE enhancement of the jet impingement cooling performance with deionized water. Shah et al. (2021) studied of the pool boiling heat transfer of R-134a/polyolester oil mixture on the surfaces having a series of pore diameter (0.1 to 0.3 mm) and pitch (0.75 to 3.0 mm) at the saturation temperatures of 4.4°C and 26.7°C and the oil concentration varied up to 5%. Thakur et al. (2021) investigated enhancement of pool boiling using multi walled carbon nanotubes based nanofluids for the recovery of the wastewater heat and incinerator heat. The CHF enhancement was found to be 62.12% more than the CHF acquired for the water.

4.2. Flow Boiling HTE

Deng et al. (2021a) reviewed recent research in flow boiling HTE and fabrication of enhanced microchannel in microchannel heat sinks. They summarized typical fabrication methods for enhanced microchannels and discussed their advantages and disadvantages, such as etching, micro-mechanical cutting, micro electrical discharge machining, laser processing, sintering, chemical vapor deposition, and 3D printing. Shi and Ruan (2021) investigated a visual power device phase change heat exchanger with a cross-sectional area of 180 mm × 20 mm to reveal the link between the bubble dynamic characteristics such as bubble generation, growth, departure, and coalescence and the flow boiling heat transfer mechanisms under different heat fluxes. Lin et al. (2021b) numerically studied flow boiling HTE behaviors of water on micro-fin, micro-cavity, and smooth surfaces in a microchannel using the VOF method, the phase change model, and solid-fluid thermal coupling in an OpenFOAM solver and analyzed the detailed HTE mechanisms of the micro-fin and micro-cavity surfaces on the heat transfer process and the influences of wettability on these surfaces.

Cui and Liu (2021) studied the flow boiling HTE of HFE-7100 in a wavy copper microchannel heat sink fabricated with the picosecond laser technique. The micro porous structures were naturally formed on the sidewall and bottom of microchannel during the laser fabrication process, which increase the wall surface roughness. Cheng and Wu (2021) designed new high-aspect-ratio groove-wall microchannels with a series of rectangular grooves etched on the plain side walls to enhance the flow boiling performance. Yarahmadi et al. (2021) studied porous medium's effects on subcooled flow boiling of water in a vertical annulus tube with an inner diameter of 50.7 mm and an outer diameter of 70.6 mm at near atmospheric pressure and analyzed the effects of different parameters such as heat flux, mass flow rate, and the inlet subcooling temperature on heat transfer coefficients. Li et al. (2021f) designed a new microchannel configuration by incorporating capillary micro-pin fin fences and multiple micro-nozzles to sustain thin liquid film evaporation and promote mixing and global liquid supply simultaneously. A new boundary layer covered with thin liquid film was activated by the capillary micro-pin fin fences along the sidewalls of the channel. Additionally, the sustainable thin liquid film was maintained using capillary effect, which could promote the capillary-driven flow inside the gap between micro-pin fin fences and the sidewalls. Ahmadi and Bigham (2021) studied the flow boiling HTE performance in gradient wick channels, which outperformed those of the homogenous wick channels and solid fin channels. Deng et al. (2021b) designed a type of open-ring pin fin microchannels and investigated flow boiling for advanced microchannel heat sinks. Zhao et al. (2021b) performed experiments to assess the two-phase and flow boiling performance of both inline and staggered open-ring pin fin microchannels with superhydrophilic (SHPi), hydrophilic (HPi) and superhydrophobic (SHPo) properties. Lv et al. (2021) investigated unstable vapor liquid two phase flow phenomena and characteristics of flow boiling with HFE-7100 in two parallel rectangular multi-microchannels with aspect ratios of 0.2364 and 0.3182 under a wide range of test conditions. Ma et al. (2021b) studied the HTE flow boiling performance in integrated sinusoidal wavy microchannels with secondary channels.

Cheng et al. (2021b) performed a comprehensive review of fundamentals and engineering applications of CO_2 flow boiling heat transfer, flow patterns, and two-phase pressure drops in macro- and micro-channel evaporators. According to their extensive analysis, the physical mechanisms and prediction models of the CO_2 flow boiling heat transfer and two-phase flow phenomena in evaporators have been well understood. Tiwari and Moharana (2021) conducted a 3D numerical study on two-phase flow boiling in rectangular microchannel with wavy vertical wall configuration for heat dissipation in high flux electronics devices. Straight and wavy microchannels were considered for comparison and analysis.

4.3. Condensation HTE

Condensation is classified into filmwise condensation and dropwise condensation. Modified surfaces are generally used to improve filmwise condensation heat transfer and to generate dropwise condensation for HTE. Ho and Leong (2021) reviewed natural convection condensation on the external surfaces of modified flat plates and tubes and forced convection condensation inside and on the modified tubes. Various models and prediction methods for the heat transfer coefficients on plain and enhanced surfaces are evaluated. Nguyen and Ahn (2021) reviewed the application of micro/nanoscale surface modification techniques in heat exchanger for HTE. In addition, the HTE mechanisms and future research directions are addressed for both single and phase change heat exchangers. Zhang et al. (2021f) developed an annular flow condensation model for binary zeotropic mixtures in the horizontal rectangular microchannel, which was validated with the experimental data for R134a/R245fa mixture in the same conditions. Gu et al. (2021) studied the HTE performance of the moist air condensation process in a 3D finned tube. Han et al. (2021a) demonstrated the crystal self-arrangement using a capillary flow to combine the advantages of the hierarchical structures and the biphilic wettability for further enhancing the condensation heat transfer. Ho et al. (2021) developed a theoretical model for filmwise condensation of steam on 3D pin fins fabricated by selective laser melting, an additive manufacturing technique considering the effects of surface tension and gravity on the liquid film flow over the pin fin surface.

Goswami et al. (2021) reviewed studies on surface wettability related to condensation HTE. While both filmwise and dropwise condensation modes are addressed in their review, emphasis was given to the enhancement of dropwise condensation which theoretically has much higher heat transfer coefficients than the filmwise condensation. They also discussed the fundamental theoretical models governing surface wetting and heat transfer in condensation and the methods to reducing wetting including coatings of low surface energy materials such as polymers, noble metals, rare-earth oxides, organic monolayers, switchable wettability surfaces, and ion-implantation. Wang et al. (2021e) proposed superhydrophobic surfaces with micropillared and nanopillared structures to enhance heat transfer at large subcoolings and experimentally investigated the influence of micropillar spacing and surface subcooling on the droplet dynamics and heat transfer using microscopic visualization techniques. In addition, they performed the microscopic modeling of condensation heat transfer on the microstructured surfaces using the mesoscopic lattice Boltzmann method. Najafpour et al. (2021) investigated condensation heat transfer on a stainless steel tube with superhydrophobic coatings produced by the electrophoretic deposition and spraying methods. Dropwise condensation regime was observed over both the coatings as a result of hydrophobicity. Chehrghani et al. (2021) investigated the behavior of condensed droplets in the presence of a vapor flow with different vapor qualities for flow condensation HTE. Zhang et al. (2021d) studied steam condensation HTE over a honeycomb-like microporous superhydrophobic surface fabricated by electrodeposition method under various condensing pressures. Stable coalescence-induced condensate droplet jumping was realized on the honeycomb-like surface with hierarchical micro-/nanostructures, leading to significant condensation HTE over that on a smooth hydrophobic surface at low degrees of subcooling. Liu et al. (2021a) investigated the key factors affecting the liquid-vapor separation process, such as the number of liquid-vapor separation devices, the wind velocity, and the total mass flow rate. They found that the in-tube pressure drop was the dominant parameter affecting the separation efficiency. This liquid-vapor separation condenser has better thermal-hydraulic performance than a serpentine condenser due to the condensation HTE in the liquid-vapor separation condenser.

5. Radiation HTE

In this section, selected studies with a focus on near-field radiation heat transfer (NFRHT) and near-field thermophotovoltaic (NF-TPV) are briefly reviewed.

5.1. Near-field Radiation HTE

Due to evanescent waves and photon tunneling, near-field radiation can greatly enhance radiation heat transfer with several orders of magnitude greater than that predicted between two blackbodies in the far-field. Therefore, great attention has been paid to the research of both theory development and applications of the NFRHT. Song et al. (2021) reviewed various theoretical methods, the unique functionalities, and the resulting applications related to multi-body NFRHT. Biehs et al. (2021) reviewed the NFRHT in many-body systems and discussed challenges and potential research directions.

Xu et al. (2021a) investigated the NFRHT of gradient refractive index slabs. The index slabs show more evanescent electromagnetic states in the lower frequency region, leading to red-shift in the near-field heat flux spectrum and enhancing local absorption inside the medium. Wei et al. (2021) designed a three-axis antenna to measure the NFRHT generated by rock fracture. The three-axis antenna shows relatively advantageous performance than the wide-band loop antenna for low-frequency signals measurement. Zhou et al. (2021) investigated the NFRHT of 2D material germanium selenide. The 2D semiconductor at a small vacuum gap can achieve a heat flux of four orders of magnitude of the black-body limit due to the strong quasi-elliptic surface plasmon polaritons at near-and midinfrared frequency regions. Tang et al. (2021a) studied the NFRHT between two separated parallel plates: graphene supported by a substrate and a magneto-optic medium. The magnitude and direction of the heat transfer flux can be controlled by the electric current and an in-plane magnetic field in the magneto-optic medium. The electric current through the graphene results in increased nonequilibrium fluctuations and induces energy transfer. Shi et al. (2021) investigated the NFRHT enhancement by manipulating coupled plasmon polariton geometry. The surface phonon polaritons enable two orders of magnitude of emission above the limit at a gap distance of approximate 50 nm. Peng et al. (2021) studied the twist-induced NFRHT enhancement between two ferromagnetic insulator slabs and found a large twist-induced thermal switch ratio in large damping conditions and nonmonotonic twist manipulation for heat transfer under small damping conditions. Taniguchi et al. (2021) studied the NFRHT via controlling magnetic polariton between a metal–insulator–metal structure and found that the near-field radiation heat flux was enhanced by approximately four times that between blackbody surfaces. Chen et al. (2021a) investigated a self-adaptive near-field radiative thermal modulation using a thermally sensitive bimaterial structure composed of gold and silicon which shows a bending tendency upon a sudden temperature change, and the NFRHT enhancement mainly depends on the separation gap between the two spaced objects. Hao and Guo (2021) introduced and defined an *F*-factor to quantify the NFRHT enhancement in a whispering-gallery mode optical sensor and revealed that this factor value matched with the sensitivity enhancement in the detection of viruses, such as respiratory viruses.

Thermal control is critically important in near-field radiative heat exchanges for complex solid architectures. Latella et al. (2021) reviewed the investigations regarding the passive and active control of near-field radiative heat exchanges. Xu et al. (2021b) developed an NFRHT assisted smart skin which can tune the heat dissipation flux accurately and in a large range for spacecraft thermal control. Tang et al. (2021b) studied a twist-induced control of the NFRHT between magnetic Weyl semimetals from the mismatch of the surface modes of the two slabs with a relative rotation due to their intrinsic nonreciprocity. Yang et al. (2021) investigated the twist-induced control employing integral twist and inter-layer twist in a multilayered black phosphorus/vacuum system.

5.2. Near-field Thermophotovoltaic

NF-TPV is an emerging technology due to their potential for high-power density and high-efficiency energy conversion systems. It can significantly intensify the performance of various systems by recovering the out-of-band photons and evanescent waves.

Jiang et al. (2021a) studied a multi-junction thermophotovoltaic system based on the NFRHT and hyperbolic metamaterial. Their system can expand the radiation spectrum to 1720-3650 nm and recover more photons. The NFRHT is also enhanced by the infinite wavevector in the hyperbolic metamaterial. Mittapally et al. (2021) investigated NF-TPV devices with thermally robust planar emitters and photovoltaic cells. Inoue et al. (2021) studied a one-chip NF-TPV device to overcome the blackbody limit. The device shows 1.5 times larger photocurrent density than the far-field limit at the same temperature, 1 to 2 orders of magnitude greater output power than some previously reported near-field systems. Chen et al. (2021b) investigated three-body NF-TPV systems integrated with an intermediate modulator between thermal emitters and photovoltaic cells and found that the output power of the three-slab system was much higher than that of the corresponding two-slab system. Dang et al. (2021) studied a three-body thermophotovoltaic system configured by a tungsten emitter, a metallic spectrum control layer, and a photovoltaic cell. The efficiency and output power were substantially improved. Chen et al. (2021c) studied a hyperbolic metamaterial based three-body NF-TPV system and found that the radiation heat flux from the emitter to the cell was enhanced by the weakly dissipating hyperbolic waveguide and the emitter emitted higher spectral heat flux located in the hyperbolic region.

Wang et al. (2021b) theoretically investigated the moderate-temperature NF-TPV systems functioning at 400-900 K. The emitters having a graphene-hexagonal-BN-graphene sandwiched structure and a double graphene-hexagonal-BN heterostructure exhibited higher output power density and energy efficiency than the near-field system based on mono graphene-hexagonal-BN heterostructure. Papadakis et al. (2021) analyzed the NF-TPV energy-conversion systems and focused on their open-circuit voltage. The thin-film near-field thermophotovoltaics had great advantage in terms of open-circuit voltage as well as conversion efficiency and power density. Li et al. (2021c) investigated the transient performance of a nanowire-based NF-TPV system, the heating process of each component in the system, and the effects of the input power density and cooling medium's velocity on the system performance. Callahan et al. (2021) developed a fully coupled iterative model of charge and radiation transport in semiconductor devices and analyzed the near-field and far-field GaSb thermophotovoltaic and thermoradiative systems. Their model can accurately simulate the photon recycling and near-field enhancement of external luminescence. Shan et al. (2021a) developed an optimization model of NF-TPV systems and investigated the effect of the operating parameters such as emitter and cell temperatures, applied voltage and vacuum gap on the system performance. Shan et al. (2021b) conducted research of optimization of an NF-TPV and thermoelectric hybrid system for energy harvest.

6. Thermal Energy and Process Intensification

Transport intensification techniques provide a powerful tool to enhance the thermal performance of heat exchangers and devices, thermal energy recovery, thermal energy storage and saving, and have critical roles in the process intensification for engineering applications. In this section, selected studies on transport enhancement techniques for thermal energy and process intensification are briefly reviewed with a focus on systems related to thermal energy recovery, thermal energy conversion, and thermal energy storage.

6.1. Thermal Energy Recovery Intensification

Heat pipe heat exchangers are widely applied in thermal energy and energy recovery systems due to their simple structure, low cost, and excellent heat transfer performance. Xu et al. (2021e) reviewed the studies of enhanced heat transfer in pulsating heat pipes in terms of working fluids, operation mechanisms, and for the applications in electronic cooling, solar collectors, waste heat recovery, and machining process. Khalid et al. (2021) experimentally studied and compared the thermal management using sintered copper wicked and grooved heat pipes and found higher capillary pressure and larger operating temperature in the sintered heat pipes. Singh and Kumar (2021) investigated the HTE of alcohol-water based self-rewetting fluid in a pulsating heat pipe. Less thermal resistance to fluid flow in the improved heat pipe was confirmed and its thermal performance was explained based on the combined effect of phenomena such as the Marangoni effect, capillary effect, and wettability. Zhang et al. (2021a) studied a novel structure of pulsating heat pipe with connected paths to achieve split flow of working fluids to augment heat transfer. Kılınç (2021) investigated the intensified performance of a thermosiphon using three different hybrid nanofluids: (MgO + ZnO), (CuO + ZnO), and (MgO + CuO). Kommuri et al. (2021) investigated the single-turn closed-loop pulsating heat pipe with an additional branch in the evaporator section to enhance the thermal performance by increasing the flow circulation in single direction.

Evaporators and condensers are key components in nearly all phase change thermal processes and thermal energy systems. Xu et al. (2021d) investigated the dropwise condensation heat transfer performance on a super-aligned carbon nanotube mesh-coated surface for improving the efficiencies of energy conversion, thermal management, water recovery, and treatment systems.

The mesh-coated surface can obviously enhance the coalescence and sweeping departure of the condensing droplets. Ng et al. (2021) investigated the phase-change HTE in a two-phase closed thermosyphon coated with graphene-nanoplatelets, and examined the HTE with different wettability. Endowed with the unique rapid water permeation property, the superhydrophilic graphene nanocapillaries spread the water film to a larger surface area which is favorable to the evaporation. Kaushik et al. (2021) conducted an experimental investigation of a vapor compression-based refrigeration cycle with two kinds of working fluid: (i) R134a and (ii) R134a + CuO nanoparticles (20-40 nm). A significant increase in the cooling capacity of the evaporator and condenser was achieved.

Nanofluids with superior thermal properties have the potential to replace the conventional coolants in engine cooling system to improve the thermal performance. Kumar and Sahoo (2021) experimentally investigated the HTE of a car radiator with a ternary hybrid nanofluid of 0.12 vol.% Al_2O_3-CuO-TiO_2 in water for air preheating in engines and waste heat recovery from the mentioned radiator. Sundar et al. (2021c) investigated water-based nanodiamond nanofluids circulating in a flat plate solar collector at different particle loadings and Reynolds numbers. Muhammad et al. (2021) investigated the enhanced heat and mass transfer of binary nanofluid in an ejector adiabatic absorber for solar energy recovery application. Herrera et al. (2021) investigated the thermal enhancement of a thermosyphon-based heat exchanger using graphene oxide nanofluid as the working fluid in a cogeneration system for waste heat recovery. The use of nanofluids showed significantly higher heat transfer coefficients than use of single-phase fluid.

The needs for energy recovery systems require a significant progress in design of high performance thermal and fluid transport equipment. Shen et al. (2021) investigated a membrane-type total heat exchanger as an air-to-air energy recovery device used in building energy conservation relating to forced ventilation. Mesgarpour et al. (2021) investigated the thermal performance of a solar air heater within a closed-cycle heat recovery system. Rednic et al. (2021) studied a two-stage heat recovery system integrated with thermoelectric elements for extraction of waste heat of exhaust flue gases from burning chamber of a Stirling engine. Gao et al. (2021a) investigated the heat transfer of flowing irregular semi-cokes in heat exchanger with the purpose to improving the waste heat recovery and utilization efficiency of high-temperature semi-cokes. Picón-Núñez and Rumbo-Arias (2021) studied the thermohydraulic performance of welded plate heat exchangers in energy recovery systems to reduce the number of units for the potential benefits in revamping projects. Han et al. (2021b) investigated seven modified tubes including floral, notched, endcross, corrugated, endcross floral, notched floral, and endcross corrugated structures for condensers of absorption refrigerators at the saturation temperature 40°C. Significant condensation HTE was achieved, especially for compound enhanced tubes. Karana et al. (2021) investigated the HTE of a compact exhaust heat exchanger with twisted tape inserts for automotive waste heat utilization. Hosseini et al. (2021) investigated the HTE in a rib-enhanced gas-gas heat exchanger used in a sponge iron production plant. Tuncer et al. (2021) investigated the HTE performance of a shell and helically coiled heat exchanger applied in refrigeration, heat recovery systems, chemical processing, heat storage, and food processing.

6.2. Thermal Energy Conversion Intensification

Thermoelectric power generation technology based on the Seebeck effect can directly converse thermal energy to electrical energy. Thermoelectric application has been extensively investigated in a wide range of areas such as aerospace facilities, transport tools, and industry utilities, etc.

Wang et al. (2021f) investigated the performance of a generator based on phase change materials and HTE in the thermoelectric application. The phase change temperature, thickness and thermal conductivity of PCM considerably impact the electrical energy generation. The surface coating can increase the absorption coefficient and lead to an increase in electrical energy. Zhong et al. (2021) investigated a nanofluidic two-phase closed thermosyphon-assisted thermoelectric generator for exploiting the thermal reservoir in underground coalfield fires. Proper addition of copper oxide nanoparticle can improve the heat transfer in the thermosyphon by 27.9%. Zhang et al. (2021c) found that the conversion efficiency of annular thermoelectric generator was higher than that of the flat-plate generator, but the output electric energy has no obvious difference. Ruan et al. (2021) assessed the cooling performance using graphene nanoplatelets nanofluids in thermoelectric cooler systems and found performance enhancement by using nanofluids and the intensification increased with increasing nanoparticle concentration. Huang et al. (2021a) investigated an automotive thermoelectric generator by using pentaerythritol as a potential energy storage material.

Fuel cells have gained increasing attention due to their high efficiency to convert the chemical energy of a fuel and an oxidizing agent into electricity through a pair of redox reactions. Liao et al. (2021) investigated a hybrid system coupling solid oxide fuel cell with thermoradiative and photovoltaic cells for energy cascade utilization. An efficiency of 0.77 through parametric optimal analysis was achieved and both the electricity production and system efficiency were improved by decreasing the leakage resistance of the solid oxide fuel cell. Sayed et al. (2021) investigated the nanofluids effect in fuel cells. The carbon-based nanofluids almost doubled the thermal performance of the fuel cells while decreasing the size of the cooling system, and thus effectively improved the electron transfer in microbial fuel cells. Nguyen and Shabani (2021) investigated the thermal management of the metal hydride hydrogen storage used in fuel cell systems and claimed that the effective thermal conductivity of the metal hydride bed should be at least 2 W/mK and the heat transfer coefficient of heating/cooling media should be in the range of 1000–1200 W/m^{2}K.

Solar photovoltaic can convert solar radiation into thermal and electrical energy but the photoelectrical efficiency is significantly influenced by the photovoltaic module temperature. For the purpose to produce more electrical power and improve the system efficiency, Navakrishnan et al. (2021) investigated a solar photovoltaic hybrid solar collector using thermal energy storage and two heat transfer fluids in electrical energy conversion. The maximum thermal and overall recovery efficiencies at constant water and airflow rates were 69.25% and 84.40%, respectively. The maximum electrical efficiency was about 22% higher than the conventional panel. The hybrid solar collector can significantly enhance the electrical power conversion by reducing the panel temperature. Long and Wang (2021) investigated a structured composite made from mixing copper powders into PDMS film as a heat sink material and found that the thermal properties of the composite were enhanced. They also performed numerical simulation to analyze the contributions from radiation and convection, respectively. Liu et al. (2021b) studied the temperature and turbidity of a solar pond indoor and outdoor. Three means including porous medium padding, covering, and solar collector assisting are combined to enhance the thermal performance of the solar pond. Shoeibi et al. (2021) reviewed the effects of simultaneous use of different methods to intensify the performance of a solar still, including the ways to increasing water temperature, such as using nanoparticles, PCM, thermoelectric heating, photovoltaic/thermal, solar collector, air heater, and electrical heater, and the methods to decreasing temperature of condensation area, such as using the glass cooling, external condenser, and thermoelectric cooling.

6.3. Thermal Energy Storage Intensification

PCMs are generally employed for making more flexible, highly efficient and reliable thermal energy systems in solar collectors, heat pumps, heat recovery, hot and cold storage systems. Punniakodi and Senthil (2021) reviewed the studies on the melting and solidification of PCM in different container geometries and their orientations for heat storage in solar thermal systems. Gadhave et al. (2021) reviewed the techniques used to improve the PCM-based LHTES. Li et al. (2021j) reviewed the latent thermal energy storage technologies with a particular focus on medium-high temperature PCM for heat recovery, storage, and utilization. Zhang et al. (2021b) nano-encapsulated phase change n-Octadecane in a poly shell, which showed good morphology, high latent enthalpy and excellent thermal stability. Elsanusi and Nsofor (2021) investigated the melting of multiple PCMs in different arrangements in a horizontally positioned heat exchanger to address renewable energy fluctuation problem. Mehryan et al. (2021) studied nano-encapsulated PCM suspension in a wavy-wall enclosure with an active rotating cylinder for applications in waste heat recovery and thermal energy storage systems. Yazici et al. (2021) employed PCM/graphite matrix composite in a tube-in-shell geometry for solar thermal energy storage and recovering waste heat applications. Yazdani et al. (2021) investigated a compact PCM-based thermal battery that employs 3D printed metal surfaces via additive manufacturing for thermal energy storage and recovery purpose. Li et al. (2021b) studied biomimetic phase change composites and showed 56.3% increase in the maximum solar-thermal energy storage efficiency compared to the base materials.

To create an energy–efficient heat pump LHTES system, Jin et al. (2021) investigated a novel sodium acetate trihydrate–potassium chloride –urea/EG composite PCM used for the heat pump energy storage system. Li et al. (2021g) developed a new shape-stabilized PCM composite for thermal energy storage intensification using the nano-encapsulated phase change material (NEPCM) embedded in copper metal foam because it combines the characteristics of high latent heat of core PCM (octadecane), shape stable from encapsulation (polystyrene) and high thermal conductivity and high area/volume ratio of copper metal foam. Farahani et al. (2021c) used a PCM (RT41) and a porous material to improve thermal performance of a solar water heater. The weather data corresponding to the installation location was adopted under three different PCM placement modes: 1) horizontally in the center of the tank, 2) under the absorber plate, and 3) as a cylindrical tube in the center of the storage tank.

Metal hydride material-based thermal energy storage systems have gained tremendous interest of research and their performance depends on selecting and matching the metal hydride pairs and the thermal management adopted. Nyamsi and Tolj (2021) investigated the impact of active and passive thermal management on the energy storage efficiency of metal hydride pairs-based heat storage systems for concentrating solar power plants or industrial waste heat recovery. A trade-off between the energy storage density and the energy storage efficiency was obtained. The active convection HTE leads to a high energy storage density but reduces the energy storage efficiency due to the increased pumping power. The passive heat transfer techniques can improve the bed’s effective thermal conductivity and provide a balance between the energy storage density and the energy efficiency.

7. Prospects for Research and Development of Future Thermal Energy, Process and Transport Intensification Technologies

Thermal energy, process and transport intensification plays a crucial role in sustainable energy technologies and achieving zero carbon emission target by 2025. Human beings are facing great challenges in environmental protection, efficient energy utilization, sustainable clean energy technologies and sustainable development in society and economy due to shortage of energy resources and greenhouse warming caused mainly by the use of fossil fuels. One of the promising methods to mitigating carbon emissions is to increase the efficiencies of energy conversion devices and systems by adopting thermal energy, process and transport intensification technologies in advanced energy systems, various processes and transport devices.

The available research of thermal energy, process and energy intensification is immense, encompassing every aspect from understanding the fundamentals, physical mechanisms, theory and practical applications of various intensification techniques to designing high performance heat and mass transfer devices, renewable energy, thermal energy, energy recovery and storage systems and evaluating these devices and systems in practical applications. Research of emerging intensification techniques is extensive in many areas such as thermal energy, energy recovery, energy storage and saving, high performance heating and cooling technology, hydrogen production and utilization, advanced heat transfer exchangers and devices, combined heat and power generation system, renewable energy technologies, etc. However, there are challenges regarding the research and applications of various intensification technologies. Development and applications of various innovative intensification techniques including advanced materials, nano coatings, nanofluids, micro- and nano-structures, enhanced tubes and microchannels and compound enhancement techniques, etc. are urgently needed.

Heat exchange elements and devices integrated with HTE techniques are widely used in practical applications. Various enhanced techniques have been adopted to intensify the heat transfer in these elements and devices, such as inserting tapes, integrating fins, nanofluids and microchannels, etc. However, some techniques will add the complexity of the heat transfer equipment and impose challenges on the operational stability and cost. Only by considering practical operation issues, such as manufacturing difficulty of inserted tapes, nanofluid compatibility, reduction of the cost and so on can ensure the successful deployment of the heat exchange elements and devices to enhance heat transfer. Compound HTE methods are widely investigated but the contribution to the heat transfer performance by each individual method and the coupled contribution to HTE by all methods are not well understood. Therefore, research is needed to further understand the fundamental heat transfer and fluid flow behaviors and to develop the design methodology of integrating HTE techniques in heat exchange elements and devices.

Nanofluids are considered to be efficient working fluids for HTE and extensively studied in fluid flow and heat transfer. There are challenges using nanofluid due to some issues such as deposition and aggregation of nanoparticles, stability, thermophysical properties, transport phenomena, theory and design methods etc. Therefore, 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.

Research on boiling and condensation HTE using micro and nano structured surfaces, microchannels, and nanofluids is extensive. In particular, emerging research of flow boiling in microchannels integrating various enhanced structures becomes popular, but systematic knowledge and physical mechanisms are lacking. Therefore, more experimental and theoretical studies are needed to reveal the fundamentals and HTE mechanisms of boiling and condensation.

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. However, fabricating and maintaining a near-field optical gap between the low bandgap photovoltaic cell and the emitter is still a challenge and more experimental studies and demonstration works are needed. Furthermore, more theoretical strategies and experimental studies of near-field thermophotovoltaic devices and systems are required to achieve high power conversion efficiency.

Regarding the research of thermal energy and process intensification, the available studies cover the aspects of working fluids, operation mechanisms and equipment design. PCMs are extensively used in a wide range of fields, such as effective thermal energy utilization, energy storage and renewable energy, etc. Research on the conductivity enhancement based on NEPCMs and nanoparticle additive PCMs, or combined and their applications in thermal various energy systems are needed, e.g., novel thermal energy storage systems such as metal hydride material-based system and high temperature energy storage systems should be studied and developed. Furthermore, more practical studies are needed to improve energy recovery and utilization in the industry and more research on maximizing life cycle asset performance should be focused on. For the thermoelectric devices, the thermoelectric conversion efficiency should be improved as it is crucial for commercialization and practical use. The mechanical strength and thermal stability of the employed materials are needed to be further investigated, and novel thermoelectric devices with high efficiency and stability from the emerging available materials should be developed.

Both conventional and emerging thermal energy, process and transport intensification technologies are crucial in achieving zero carbon target by 2050. From this literature survey, extensive research on thermal energy and process intensification has been conducted to develop new methods, understand and develop the fundamentals and practical applications. However, there are big challenges in the development, research and implementation of various intensification techniques, yet these have provided new opportunities to investigating and developing innovative technologies in thermal energy system, advanced thermal energy storage, hydrogen production, storage and systems, renewable energy, high heat flux cooling technology, advanced thermal and power energy generation systems and zero carbon process and thermal energy systems, industrial and civil applications. Many aspects of conventional and innovative heat transfer enhancement techniques such as systematic knowledge, theory, physical mechanisms, materials, design methodology and engineering applications are urgently needed to be achieved through extensive and cross-boundary research and engineering practice.

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