Chapter

Applications of Heat Transfer Enhancement Techniques: A State-of-the-Art Review

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Abstract

The fundamentals of heat transfer and its applications, the classification of heat transfer technology and different heat transfer techniques, and the needs for augmentation and its benefits and the different combinations of two or more inserts and integral roughness elements for heat transfer augmentation purpose have been introduced and discussed in this chapter. It is shown that most of the compound techniques performed better than the individual inserts for heat transfer enhancement. This chapter has also been dedicated to understanding the basic concepts of vortex generators for heat transfer enhancement in plate-fin heat exchangers. The performance of transverse, longitudinal, and wing-type vortex generators has been discussed as well.

Keywords: heat transfer, review, enhancement, heat exchanger, vortex generators, twisted tape, ribs, combine techniques

1. Introduction

The phenomenon of heat transfer has always been a topic of interest to researchers and manufacturers alike. The previous researchers have addressed heat transfer characteristics of wide varieties of fields like bio-heat transfer, semiconductors, various cooling techniques, and natural phenomenon like oceanic currents and other important and relevant areas.

This chapter aims to cover all the relevant research papers about heat transfer published till 2018; few are there containing numerical and analytical aspects of heat transfer, while others are highlighted for its applications in engineering.

2. Free stream and flows over a surface

The chapters have been classified into categories like compressible and high-speed flows, externally influenced flows, flow related to films and interfaces, instable flow effects, flows with special fluid types, and flow related to reactions.

2.1 Effect of external surface

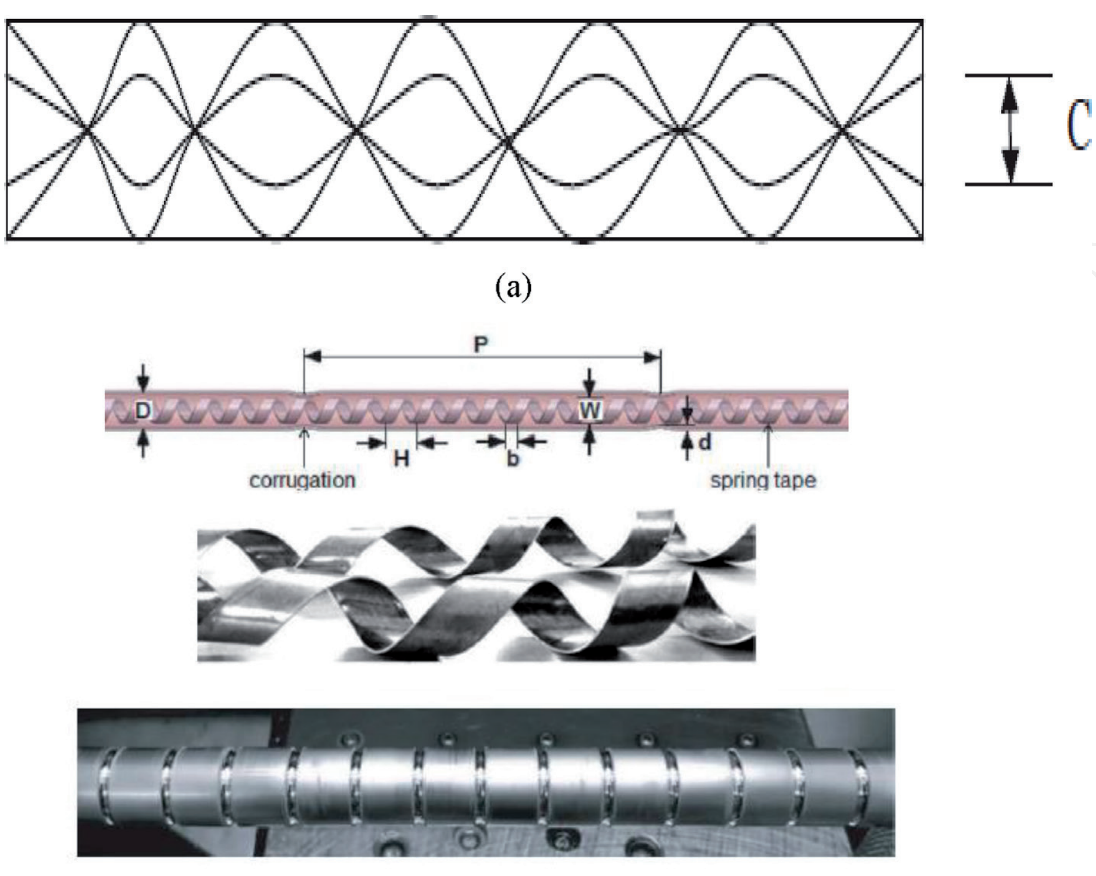
The effect of turbulence on free stream during heat transfer enhancement caused by the destruction of the viscous sublayer in the gaseous cavitation of CO_2-saturated water was recognized. The influence of roughness and wall temperature on the turbulent boundary layers was investigated [1, 2]. A model was developed to evaluate fluxes in urban boundary layers using the naphthalene sublimation technique [3].

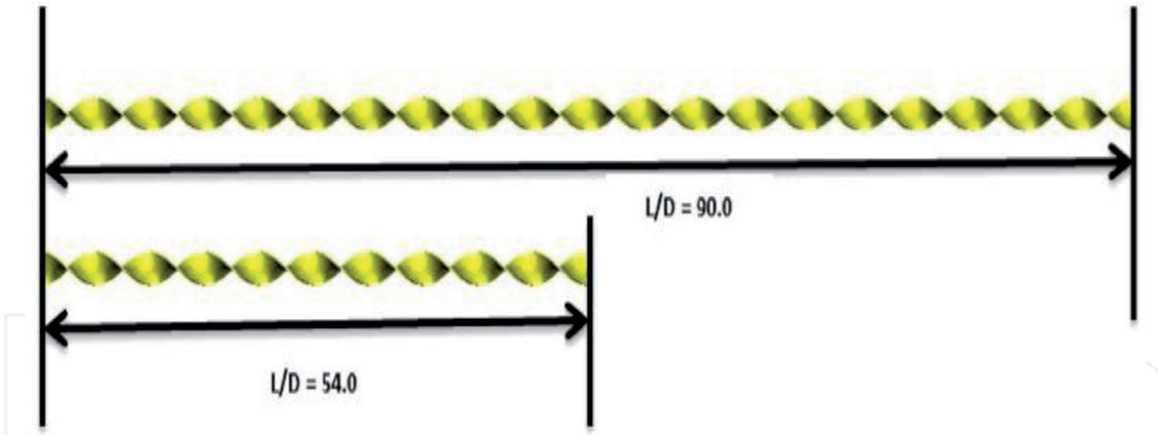
2.2 Effect of geometry

Heat transfer enhancement is the process of improving the rate of heat deposition or removal on a surface. It is a subject of interest to the researchers as it results in savings in energy as well as cost. Heat transfer can be enhanced by using different types of swirl generators. Geometry plays a vital role in heat transfer enhancement. Transverse ribs with twisted tape and helical tape; axial rib with screw tape; and inclined limb in cylindrical dust have been studied for friction factor and Nusselt number [4–8]. Heat transfer augmentation techniques have been used to the study the effect of heat transfer and pressure drop due to insertion of twisted tape, inclined turbulator, corrugated tube with spring tape, diamond shape cylinder, wavy turbulator for short length and full length, center-trimmed twisted tape, flow around hexagonal cylinder, wavy channel, rhombus duct, square duct, and double pipe [9–20] as shown in **Figure 1**.

2.3 High-speed flow

A computational fluid dynamic (CFD) model has been developed to understand the hypersonic flow fields for reentry vehicles; facility was created for modeling

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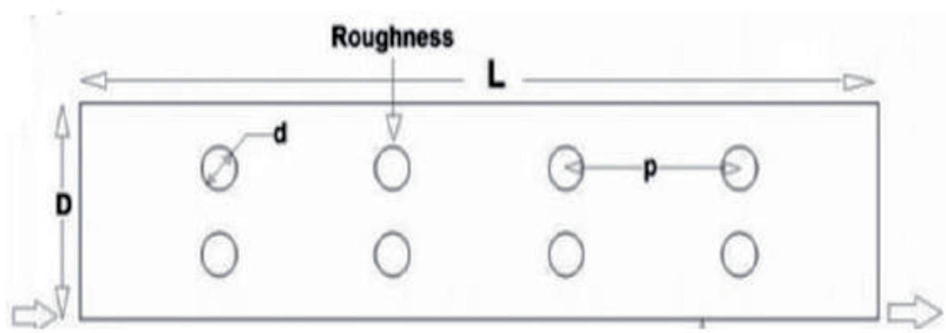
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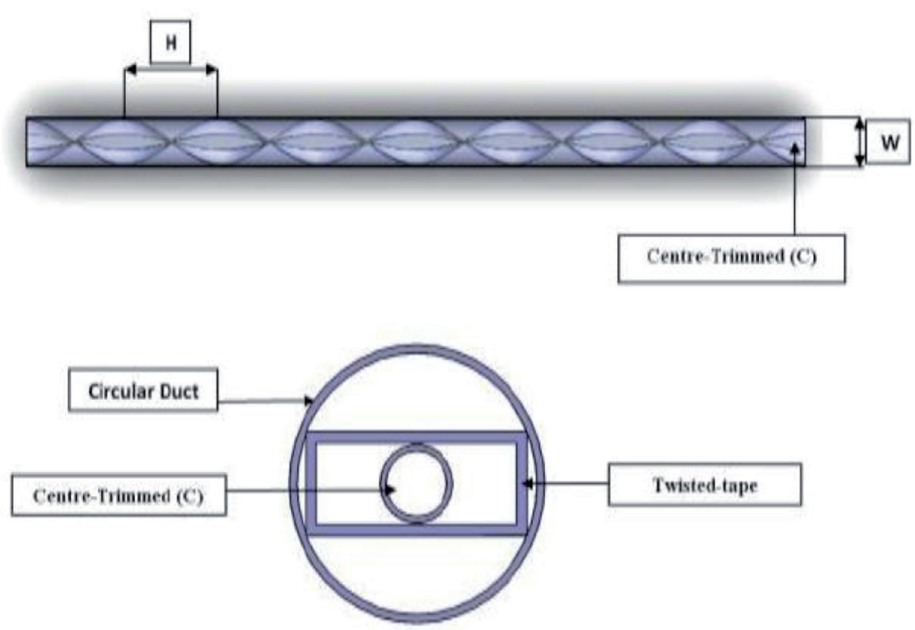
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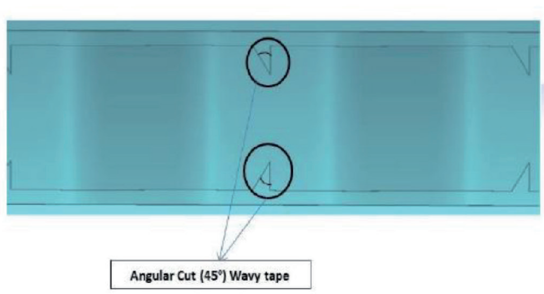
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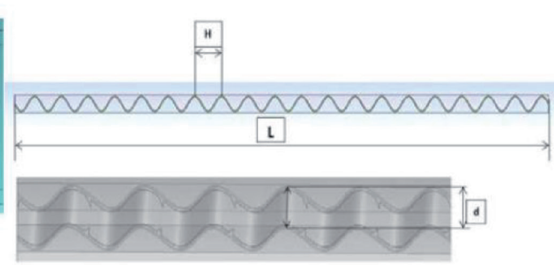
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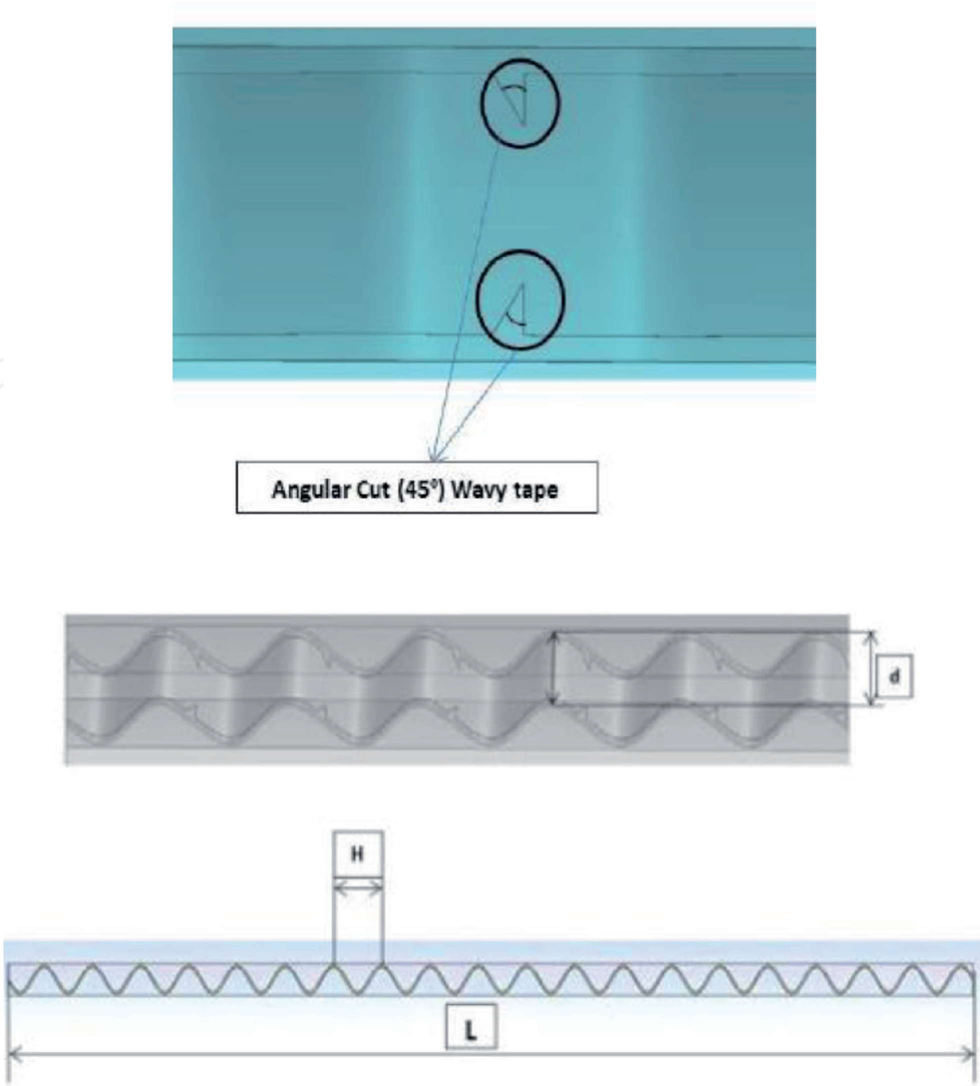

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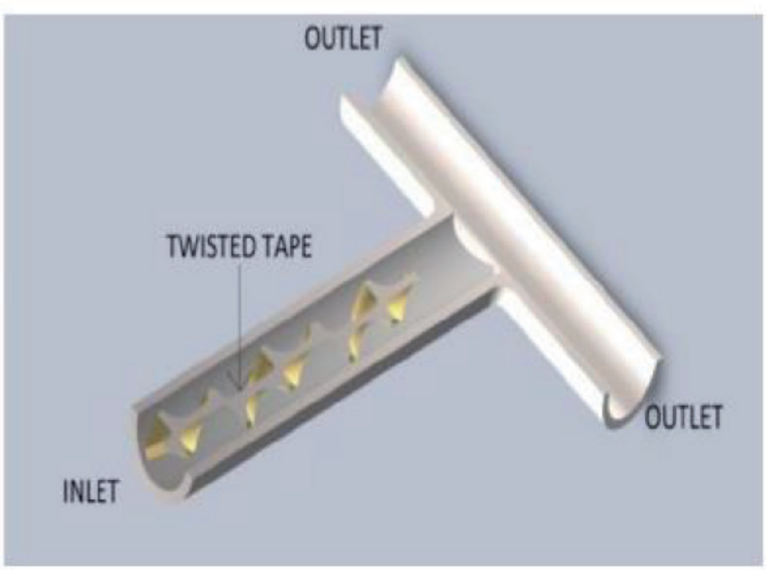

(g)

Figure 1.
Different types of vortex generators used for enhancement of heat transfer. (a) Center-cleared twisted tape [4]. (b) Spring tape insert [9]. (c) Twisted tape [10]. (d) Swirl generator [12]. (e) Twisted tape with clearance at the center [13]. (f) Wavy tape with angular cuts [14]. (g) Full-length twisted tape [16].

the projectile flight heating upon reentry. Simulation model for heat transfer due to convection and heat penetration was proposed [21], and comparative study has been conducted using of the European Atmospheric Reentry Demonstrator.

3. Channel flows

3.1 Straight wall passage

Initially, thermal characteristics in straight wall passages have been considered to analyze the heat transfer phenomenon in channel flows. Using the finite elements method, Nusselt number and friction factor were calculated for laminar regime. An investigation on laminar-turbulent transition inside a heated horizontal tube was conducted [22]. An analytical study for joule heating in a parallel plate channel with thermally developed flow has been conducted [23]. A circular tube was examined using various different conditions for viscous flow [24]. A novel method was developed for evaluating the Nusselt number for hydrodynamic flow conditions [25]. Horizontal, inclined channels and vertical plane passages were examined for mixed convective heat transfer [26, 27]. A prediction was presented for Nusselt number for the in-tube cooling of supercritical carbon dioxide [28].

3.2 Microscale heat transfer

The study of fine scale heat transfer was done with various channel configurations. 3D flow and heat transfer were examined in microchannels [29]. Theoretical analysis for heat transfer in laminar flow between two parallel plates separated by a very small space in micron range was conducted. The momentum and energy equations are solved for the hydraulic and fully developed thermal flow in the microchannel [30]. This method was also used to simulate rarefied gas flow and heat transfer in microchannels in a particular Knudsen number range [31]. Water was used as the working fluid in microchannel of rectangular shaped heat sinks, and computational studies were carried out [32]; also, their thermal performance was optimized minus water [33]. Convective heat transfer of fully developed flow both thermally and hydrodynamically in a rectangular microchannel is investigated [34]. A simulation model of low-power microchannel thermal reactor was presented [35]. Fractal branching used for the cooling of electronic chips was investigated [36]. Slotted microchannels were studied analytically on the basis of conduction and convection [37]. The performance of thermal fluid in a small capillary was studied experimentally [38].

3.3 Irregular geometries

A variety of papers covering numerous geometries have been taken into consideration in this section. Narrow-spaced fuel element configuration in multichannel was modeled numerically [39]. Rhombus and ellipse shape ducts were studied using Galerkin integral method [40, 41]. The heat transfer in a pin fin at the end of the wall was investigated [42]. The heat transfer in a milliscale thrust nozzle was studied numerically [43]. Viscous flow convections and heat transfer were studied in corrugated ducts [44]. For square ducts a combined study was undertaken to understand the thermal characteristics in different shapes [45]. Experimental study was done with regard to two-pass internal coolant passages in gas turbines [46]. An increase in heat transfer due to rolling and pitching action in swirling ducts was found experimentally [47]. Flow and heat transfer for metal honeycomb geometry was inspected [48]. The effect of viscous forced convection in branching ducts was studied [49].

4. Flow separation

A study showing the separation of energy in free shear zone was carried out, and the role of pressure in the flow separation was studied [50]. In vertical ducts and other cross sections, mixed convection was investigated numerically [51]. Three-dimensional flow studies for understanding the effect of step height were also available. Large eddy simulation (LES) was undertaken for the turbulent flow over a backward-facing step [52]. A laminar airfoil was taken, and adiabatic and heating conditions were investigated at modest subsonic Mach numbers [53]. Correlations among the heat transfer coefficients of dull-edged flat plates and square channels were studied [54]. A finite volume method was used to investigate the 2D natural convection in a heated cylinder, and the significance of aspect ratio, Prandtl number, and boundary conditions on thermal characteristics were studied [55].

5. Experimental methods

Precise measurement results in good outcome in every research work. In heat transfer, measurement plays a pivotal role in the analysis of thermal system. Even after the numerical modeling of a heat flow system, it is not possible to define all the parameters with full accuracy leading to the failure of many thermal systems. This includes most of the engineering devices such as spacecraft, cryogenic engines, satellites, etc. Modeling of a turbulent flow and transition zone is very complicated, and hence it is difficult to predict very accurately. For the accuracy and relevancy of data, precise measurement is required which gives rise to the development of precise system with better accuracy.

5.1 Heat transfer

Heat flux measurement is an important aspect for understanding the physics related to transport of heat; distinguish among conduction, convection, and radiation mechanism; analyze energy balance; derive material properties; and understand the flow regimes, etc. The physical and mathematical models are presented to investigate the evolution of surface waves for free-falling turbulent wavy films with varying Reynolds number [56]. Thermochromic liquid crystal (TLC) is one of the best techniques to visualize the transient heat flow over the surface. The change in color of TLC from red to green to blue helps understand the flow of heat flux over a surface in supersonic wind tunnel [57]. Luminescent coating is another option for measurement of heat flow over a surface. The method has been used to determine the heat flow in shorter duration of less than 10 ms hypersonic flow [58]. Heater foils can be used to measure the bulk temperature development in time-based heat flow measurement by using a simplified model in which temperature development has been characterized [59].

5.2 Temperature measurement

For the temperature measurement during rapid contact solidification at the surface of substrate, an interfacial temperature sensor of 1 μm diameter has been fabricated [60]. A telecentric objective has been used for the first time to phase out the dependence on the angles in color determination in fluid-based TLCs for precision measurement [61]. An acoustic thermal scan has been evaluated using numerical methodology to evaluate the spatial resolution [62].

5.3 Velocity measurement

A multiple hot-film sensor (MHFS) arrays were used to evaluate the skin friction along the surfaces of two-dimensional streamlined objects (circular cylinder) [63]. A high time resolution ultrasonic velocity profiler (UVP) system has been developed to determine 1D velocity profile on an ultrasonic beamline [64]. A numerical investigation [65] was conducted to determine the thermal response of hot wire for the measurement of sudden shift in the velocity in turbulent flow.

5.4 Miscellaneous

Bubble cluster pattern has been reported in the turbulent bubbly flow using rake of resistive flow and signal processing associated with it [66]. Air and liquid flows have been measured individually in two-phase air liquid flow [67]. Ultrasound Doppler velocimetry has been used to measure the thickness and velocity of the liquid film [68]. A novel pressure-sensitive paint (PSP) has been formulated and used for pressure measurement in cryogenic wind tunnel [69]. A high-sensitivity thermal conductivity detector has been developed from different materials which can be used in the diagnosis of fault in transformer, oil exploration, etc. [70].

6. Phase change

This part of the chapter deals with melting and freezing of materials. The section is divided into several subsections such as phase change materials (PCMs); formation of ice and its melting; melting and freezing of radial objects; melting and solidification of metals, nonmetals, and composites; crystallization; and globule, spray, and plunge cooling for better understanding.

6.1 Phase change materials

The inability to recover latent heat after super cooling of PCMs has been pointed out, and the method to recover latent heat has been discussed [71]. The melting mechanism of PCMs in magnetic field in low-gravity atmosphere has been discussed [72]. Other works include fabrication of carbon brushes which can be used to enhance the thermal conductivity in phase change materials, the role of ultrasonic vibration on melting characterization of PCMs, and detailed examination of solid liquid phase change heat flow enhancement.

6.2 Formation of ice and its melting

Researches on the formation of ice and its melting include the thermal behavior of ice under constant heat flow per unit area and melt removal, melting of ice using natural convection, ice making by cooling water-oil emulsion with stirring, and numerical simulation of melting of ice in water under the influence of natural convection and cooling effect produced by melting of ice [73–75].

6.3 Melting and freezing of radial objects

A lot of work has been presented on phase change in radial objects such as sphere, cylinders, and slabs. A mathematical model using numerical analysis has been developed to study the melting process of PCMs in sphere [76]. A novel packed bed of spheres has been developed using graphite/PCM composite for increasing the thermal conductivity which resulted in reduction in melting and freezing time significantly [77].

6.4 Melting and solidification of metals, non-metals, and composites

It has been observed that the supercooling properties of sodium acetate trihydrate can be improved by addition of nano-Cu [78]. A simulation model of melting and solidification of PCM in metallic porous foam has been investigated in the heat exchanger. The Hunt-Trivedi model has been used to simulate the solidification process of AISI 304 stainless steel [79].

6.5 Crystal growth

The crystal growth involves controlled growth of microstructure using optical heating, modeling of mass crystallization in magma chamber, effect of crystal growth on solute distribution, and simulation of crystal growth for binary melting process [80, 81].

6.6 Globules, spray, and plunge cooling

This subsection deals with the deposition of metal droplets on the premolten pool and wavy surfaces, numerical analysis using FEM to study fluid mechanics and heat transfer of solder droplet on flat surface, numerical analysis of microdroplet deposition over a novel micromanufacturing process, and utilization of impulse atomization technique to produce controlled size droplets [82–84].

7. Numerical methods

Numerical methods are used to develop the mathematical models to solve complex numerical problems. The technique is used widely in research for modeling and optimization of the physical work which otherwise required rigorous work. The research work done in the field of heat transfer using numerical methods has been depicted in this section.

7.1 Heat conduction

A hybrid 3D model has been developed for the analysis of transient heat conduction in a functionally graded material (FGM) using generalized finite difference method [85], Cattaneo-Vernotte model (CV model) was used to develop numerical simulation of non-Fourier heat conduction for a fin attached to a microelectronic surface [86], Galerkin-vector theory and numerical method are used to develop a mathematical model to study heat conduction in nonhomogenous materials [87], and heat conduction model was developed using numerical methods to understand the flow of heat in the granular materials [88].

7.2 Inverse analysis

Systematic and local error has been identified using WKB method through numerical analysis [89], numerical inverse Laplace transform was used to solve nonlinear differential Equation [90], and numerical inverse method has been developed to extract heat flux in heat-sensitive coating region [91].

7.3 Fluid flow

The lattice Boltzmann method is used for simulation model of non-Newtonian fluid flow, two fluid method, and discrete particle method used for simulating the gas-solid flow of rough particles. A CFD model can be used effectively to study the hydrofluidization freezing, and a numerical simulation of fluid flow with thermal hydraulic mechanical coupling method on an uneven surface was developed [89].

7.4 Turbulent flow

Numerical methods can also be utilized to predict the turbulent flow. k-ϵ and LES model were used to study turbulent flow field around rows of tree and building, turbulence in flow field and temperature can be predicted, renormalization is used to determine the eddy diffusion in turbulence flow, intermittency model was developed for studying the laminar boundary transition at supersonic and hypersonic condition, and LES is used to forecast the heat transfer coefficient and blade metal temperature [92].

8. Heat exchanger and thermosyphons

8.1 Applications

The sheer variety of heat transfer operations has been demonstrated by a number of researchers in their works dealing with thermoacoustic and thermoelectric devices, rotating heat exchangers, commercial blood oxygenators, soil and deep bore heat exchangers, space craft radiators, and pressurized bubble columns.

8.2 Enhancement of heat transfer

The procedure to ease heat transfer has been stated by many researchers. The fin technology of extension is quite prevalent in the recent times. An investigation was carried out with fin tubes using liquid crystal display technology and plate finned tube exchanger by infrared thermal imaging, and performance measurement has been reported for a finned tube surface and annular fins. Fins having curly surfaces are examined for humid airflow. In addition to this film-wise condensation on plane low finned tubes, transient conduction in a fin, performance of extruded-serrated and extruded-finned tube bundles, and the features of a multi-pass heat exchanger have also been reported.

8.3 Microscale heat transfer

A number of applications now employ miniaturization of heat transfer devices: micro-heat pipe arrays, electronic cooling, microturbine, evaporation and boiling in microfin, microheat pipes, microscale temperature measurements, and modeling of microchannel flows [93].

8.4 Effect of fouling

An investigation has been done to study the effect of gas-side fouling in cross flow. Calcium carbonate fouling effect was studied with a microscale image; mineral fouling in extended tube heat exchangers was studied; the use of polyacrylic acid as anti-scaling and antifouling agent was studied [94–96].

8.5 Systems based on thermosyphon

Thermosyphons found applications in a variety of heat transfer complications such as space radiators and cooling of structures, solar water heaters, nuclear reactors and system based on geothermal energy, evaporators, preheaters, tiny heat pipes used to cool PC, laptops, and other electronic components [97–100].

9. Heat transfer: general applications

The relationship between the parameters of a fluidized bed and the heat transfer to a body engulf in it [101]. The SIMPLE algorithm [102] was used to simulate a blast furnace, and a relationship has been developed for the heat transfer coefficients on extension walls and hydrowalls of the boilers [103]. A porous radiant recirculated burner (PRRB) concept is developed to reduce losses due to open-flame combustion [104]. Leong studied the effect of latent heat of fusion on thin plates and numerical analysis of temperature change in biscuits using Monte Carlo (MC) method [105].

Multiple papers investigated the thermohydraulics of the cooling flow in nuclear reactors. A model was developed to study heat flux for low flow rates [106]. Interwrapper flow was studied, and its effects were analyzed numerically [107]. In the case of ceramic-coated turbine blades, the heat transfer coefficient does not significantly affect metal temperatures when thermal radiation is in the picture.

10. Insolation

10.1 Solar radiation

Various perspectives to evaluate solar data using modified modeling have been conducted by researchers. A new correlation between sunshine duration and radiation on the surface of the earth has been derived by Suehrcke [108]. It was found that the correlation is very well established for average value. A correction factor was proposed by Muneer [109] for calibrating the shadow band pyranometer. A model was using upper air humidity to estimate global solar radiation [110].

10.2 Solar air heater

Numerical solutions were also developed for absorbers in a porous medium, Nusselt number and Reynolds-Rayleigh number correlations for natural convection in an open-ended rectangular channel and models for solar air heater with fins [111]. Collector efficiency was predicted in a simplified manner.

10.3 Solar water heaters

Novelties in the design of solar water heating application are presented in this subsection. Fourier transform technique has been used to estimate the heat transfer and efficiency of a flat solar plate collector [112]. Double-sided flat plate collector was used to experimentally investigate the reduction in heat losses in comparison to conventional solar collector [113]. An experimental investigation on ICS solar water heart with compound parabolic concentrating integral collector storage system was designed and tested [114]. A 2D concentrator was developed aiming to store solar energy [115].

11. Plasma heat transfer and MHD

11.1 Investigation and application

In this section, heat transfer in thermal plasma reactor for nanoparticle synthesis has been investigated through different models [116]. A 3D model of heat transfer in thermal plasma system has been developed to show 3D effect of carrier gas [117]; effects of nucleation temperature were investigated by radio frequency; 2D numerical simulation was developed to show flow and heat transfer in argon gas plasma, temperature gradient, velocity, and concentration to study the nitridation of $MoSi_2$ which was carried in thermal plasma reactor; and numerical simulation model was developed to show the effect of radial injection of gas (with and without swirl) on flow and temperature field [118]. Plasma induced between two electrodes with and without swirl has been investigated for heat transfer with fluid flow [119].

11.2 Magnetohydrodynamics (MHD)

A simple monoenergetic operator and the Bhatnagar-Gross-Krook model were presented to estimate heat transfer in a rare gas between parallel plates [120]. A mathematical model of 2D magnetohydrodynamic Prandtl fluid flow over a sheet is examined [121], 3D magnetohydrodynamic Cauchy problem has been investigated [122], 2D pseudo-steady compressible magnetohydrodynamic system is studied for expansion of gas in vacuum [123], bio-convection flow of nanofluid is studied in magnetic field [124], and numerical analysis of MHD flow over vertical rotating cone is investigated. Also, the volume of fluid method is used to investigate the MHD of incompressible flow, and MHD fluid behavior is studied for flow and heat transfer [125].

12. Conclusion

In this review article, an effort has been made to study the recent development in the field of heat transfer enhancement. A lot of experimental and numerical research have been done to study the aspect of heat transfer in different fields such as channel flow, crystal growth, heat exchangers, thermosyphons, phase change materials, temperature and velocity measurement, solar energy, etc. The effect of geometry such as channel modification through inserts, roughness, etc. and external power such as magnetic field, electric field, ultrasound, etc. on the thermal performance and augmentation of heat transfer has been studied. In addition to this, the lattice Boltzmann method, WKB method, numerical inverse method, k-epsilon, Cattaneo-Vernotte model, Hunt-Trivedi model, and LES model have been studied for different heat transfer applications. Overall this review gives a full-scale summary of heat transfer applications.

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