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Review on Analysis of Heat Transfer and Fluid Flow Characteristics in Corrugated Duct

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ABSTRACT

The improvements and the enhancements in all the heat transfer systems are mainly purposed for energy savings and cost reduction in capital investment, through decreasing the costs. In the current study I made a focus on researcher's efforts in research and developments for corrugated profiles and use of nano fluids in heat transfer systems. In thermal systems heat exchangers are widely used for different engineering fields and applications. Corrugated plate heat exchangers are used by research reactors due to their easiness in assemblage/disassembly and their easy maintainability. The corrugated plate heat exchanger has a great tractability than the other types of heat exchangers; both its heat transfer area and its flow rate could be increased or decreased easily, so; it is commonly used for expansion and improvement works. Corrugation in the heat exchanger results in increase of turbulence intensity in the working fluids leading to enhanced heat transfer rates. The current revision incorporated different topics like; the corrugated surface heat exchanger structure, thermal performance, heat transfer enhancement mechanisms, flow characteristics. Also; the corrugated profile heat exchanger thermal performance and pressure drop behaviors when using nano-fluids were discussed in the current revision.

Keywords:Heat transfer augmentation, convective heat transfer coefficient, heat exchanger, corrugated duct, duct geometry, Reynold’s number

1. Introduction

The main objective of any designer is that thermal system should transmit more amount of heat transfer with minimum cost. For achieving high efficiency, the rate of heat transfer between the fluid and metal should be maximum. The one way to enhance it is by increasing the surface area of heat transfer surface. Heat transfer enhancement includes increment in the heat transfer rate and thermohydraulic performance of a system using innumerable methods. The methods of heat transfer enhancement are employed for increasing the heat transfer without affecting the overall performance of the systems significantly, and it covers an extensive range of areas where heat exchangers are used for such functions as air-conditioning, refrigeration, food industry, sewage decomposition system, central heating systems, cooling automotive components, and many uses in the industry.

There are basically three methods to enhance the heat transfer rate i.e. passive method, active method and compound method. Active methods include external power input for the improvement of heat transfer. The active method includes addition of nano sized particles having high thermal conductivity, and metallic powder to the base fluid, to increase the heat transfer rate. Passive methods do not require any additional energy rather, geometry or surface of the flow channel is modified to increase the thermo-hydraulic performance of the systems. Also two or more active and passive methods can be used combined to increase the heat transfer rate of the system and method called as compound method. Compound method have more heat transfer enhancement as compared to active and passive method.

The turbulence intensity increases due to corrugation of the surface and deliver mechanical rigidity which is one of the passive method for heat transfer augmentation. The main advantage of corrugated surface is it increases heat transfer rate, minimize fouling factor, reduces service cost and can make compact design by optimum geometry. There are three parameters to increase the heat transfer rate in heat transfer enhancement process. One of them is the providing smaller corss sectional area for free flow to increase fluid velocity results in reduction of the thickness of the laminar sublayer. A

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second parameter is the changing geometry of surface such as corrugation, use of fins which cause increased local turbulence, and the third option consists in the use of mechanical inserts that encourage local turbulence. According to thermos-hydraulic characteristics the objective of thermal system is to increase the heat load for the consider heat transfer area within the limitations enforced by the allowed pressure drop. For these objectives to be met, it follows that any heat transfer enhancement technique must improve on the heat transfer coefficient and Nusslet number and decrease in the heat transfer area for the same pumping power.

2. Literature review

2.1 Effect of geometrical parameters

N. Tokgoz et al. [1] has numerically and experimentally determine the flow characteristics and thermal efficiency in various ducts geometries. The analysis conducted for Reynolds numbers in the range of $3\times10^3 \leqslant \mathrm{Re} \leqslant 6\times10^3$. Initially, effect of aspect ratio has been examined on heat transfer enhancement and flow structures. Later on, corrugated duct geometries were designed for three different cases such as S/H = 0.1, 0.2 and 0.3. Then numerically examined the thermal efficiency of three geometries in order to optimize the aspect ratio. It has been observed that, with increase in the corrugation height, the rate of turbulence intensity on the axis of corrugated channel increases and heat transfer rate also increases and it shows a maximum values at S/H = 0.3 that corresponding to the highest aspect ratio. It has been also seen that highest friction factor occurs at aspect ratio of 0.3, followed by 0.2 and 0.1 respectively. C. C. Wang and C. K. Chen et al. [2] has done the study of the rates of heat transfer for flow through a sinusoidally curved converging–diverging channel using a simple coordinate transformation method and the spline alternating–direction implicit method. The parameters have been varied such as the effects of the wavy geometry, Reynolds number and Prandtl number on the skin–friction and Nusselt number. The analysis show that the amplitudes of the Nusselt number and the skin–friction coefficient increase with an increase in the Reynolds number and the amplitude – wavelength ratio. At a sufficiently larger value of amplitude wavelength ratio and at higher Reynolds numbers, the corrugated channel will be seen to be an effective heat transfer enhancement. To solve the flow patterns and the heat transfer characteristics, the spline alternating direction implicit method was then used.

Dogan Engin [3] studied numerically effect of cross–corrugated triangular channels having rectangle baffles with different settlement angles on thermo–hydraulic characteristics of plate fin heat exchangers. The parameters were taken as constant rectangle baffle height 0.5 H, apex angle of 60°, rectangle baffle settlement angles were 30°, 45°, 60° and 90° with Reynolds number ranging from 1000 to 6000. While wall surface temperature of the lower corrugated duct was 373K and working fluid temperature (air) was 293K. It was observed that as rectangle baffle angle and Reynolds number increased the vortex intensities in the corrugations increases. Also, thermal–hydraulic performance factor (PEC) of 45° baffle was 24.64% greater compared to 90° for Reynolds number of 6000 and the pressure drop was drop was 65.97% inferior in the corrugated triangular channel with 60° rectangle baffle angle compared of 90° angle. Limin Wang et al. [4] used the multi objectives genetic algorithm to obtain the optimal values of the height and pitch of undulated plate and the height of the corrugated plate by using the Pareto optimal strategy, to achieve a maximum heat transfer capability and a minimum pumping power for corrugated undulated heat transfer surfaces. In this study, computational fluid dynamics simulation, support vector machine and the fast non dominated sorting genetic algorithm were combined together and used for the optimization process. Numerical simulation were done to investigate the effect of geometrical parameters. It has been found that, maximum deviation for the Nusselt number and friction factor between the simulation and the published data were 8.81% and 13.1% respectively when the Reynolds number ranging from 1500 to 10,000. The comparative study between support vector machine predictions and CFD results showed that support vector machine model could predict the numerical data with good accuracy.

J.I. Corcolesa et al. [5] studied numerically effect of spirally corrugated tubes on the heat transfer and flow patterns having turbulent flow with Reynolds number ($\mathrm{Re} = 25\times10^3$). This study performed a high cost numerical simulation using a computational domain with a length of the tube (L = 2m). The corrugation shape factor (CSF) non–dimensional parameter was projected in this study which considered the width of the corrugation, a geometrical dimension removed in other studies. The turbulence model was crated with tetrahedral mesh grid. It was analyzed that pressure drop and Nusselt number decreases with increasing P/D (pitch to inner tube diameter) ratio as well as both parameters increases with increment in H/D (height to inner tube diameter) ratio, SI (Severity Index) and CSF (corrugation shape factor). It was found that corrugation shape factor enhanced from 8.3 to 13.2 (22mm), from 6 to 15.5 (12mm) and from 3.6 to 18.0 (18mm), Nusselt number increased 6%, 9% and 16% respectively. Giampietro Fabbri [6] studied the heat transfer characteristics in a channel composed of a smooth and a corrugated wall for laminar flow conditions. With the finite element model, the velocity and temperature distributions were determined. The heat transfer characteristics performance of the corrugated wall channel is compared with that of a smooth wall duct. The numerical model was used in a genetic algorithm to increase the heat transfer by optimizing the corrugation profile geometry, for pressure drop in the channel and given volume of the corrugated wall and finally at the end, presented optimum corrugation profiles. The results showed that, corrugated wall profile only maximizes the heat transfer when both the Reynolds and Prandtl numbers are not too low, when no constraint is imposed either on the pressure drop and wall volume. It has been found that, the optimum corrugated wall profile by the genetic algorithm provides a nearly 8% increment with respect to the heat dissipated by the optimum flat wall profile.

T. A. Rush et al. [7] investigated flow behavior and local heat transfer for laminar and transitional flows in sinusoidal wavy passages. The experiments has been carried out with channel aspect ratio of 10:1 bound by two wavy walls and the walls were from 12 to 14 wavelengths long, and the wave amplitude, phase angle, and wall to wall spacing were varied during the experiments. The flow was characterized as steady or unsteady, with special attention directed toward detecting the onset of macroscopic mixing in the flow using visualization methods. It was found that the location of the onset of mixing depend on the Reynolds number and channel geometry. The investigation showed that instabilities were noticeable near the channel exit at low Reynolds numbers (Re ~ 200) and move toward the channel entrance as the Reynolds number is increased; the complete channel reveals unsteady, macroscopic mixing at moderate Reynolds numbers (Re ~ 800). N. Piroozfam et al. [8] numerically studied the effect of channel geometry, geometry of obstacles in the channel, frequency and amplitude of corrugated plate and other factors in counter flow heat exchanger and its effect on heat transfer and hydrodynamic characteristics. To study the effect of obstacles in channel rectangular, triangular, and semicircular along with edge obstacles. Among all four obstacles rectangular obstacle have highest increment in Nusselt number, friction factor along with pressure drop due to increase in heat transfer surface. The rectangular obstacle causes highest heat transfer nearly 16 – 18% whereas semicircular have lowest heat transfer rate nearly 8%. The last method includes the use of pulsing flow and elastic mid–plate which causes turbulence in flow which increases heat transfer rate nearly 3 to 4 times. It was investigated that among all methods elastic plate with cold pulsed input flow improves performance of counter flow heat exchanger nearly 40 – 50% due to improvement in heat transfer rate.

A. Hasanpour et al. [9] experimentally investigated heat transfer and friction factor in a double pipe heat exchanger which has an inner corrugated tube filled with different types of twisted tapes from conventional to modified types which were perforated, V–cut and U–cut types. The twist ratios taken as 3, 5 and 7 whereas the hole diameter ratio were consider to be 0.11 and 0.33. The width and depth ratio of the cuts going from 0.3 to 0.6 taken and the Reynolds number having range of 5000 to 15,000 for a turbulent regime. The results of heat transfer and pressure drop showed that Nusselt number and friction factor for all cases of twisted tape corrugated tube are greater than the empty corrugated tube. It was also found that, ratio of friction factor for all cases of modified twisted tapes to the friction factor of typical tapes twisted in corrugated tube is higher than one except the pierced one. Kitti Nilpueng et al. [10] experimentally investigated sinusoidal wavy plate fin with and without crosscut with effect of phase shift, air velocity, heat sink base surface temperature on heat transfer coefficient, and pressure drop of airflow and its influence on heat transfer and hydrodynamic characteristics. Sinusoidal wavy plate fin with wave length of 18.68mm, amplitude of 2mm with phase shift 0^0, 90^0 and 180^0 studied with heat sink base surface temperature of 70^0C, 90^0C and 110^0C. It was observed that, with the increase in the phase shift between sinusoidal wavy walls leads to the enhancement of heat transfer coefficient by about 6.8 – 30.7%. The pressure drop increases with increasing air velocity and phase shift, about 21.4 – 40.1% as the phase shift increases compared with a phase shift of 0^0. Comparison under the same phase shift reveals that the Nusselt number and pressure drop of cross cut sinusoidal wavy plate fin heat sinks were higher than those of sinusoidal wavy fin heat sinks by about 5.9 – 19.1% and 12.38 – 20.34%, respectively.

Jixiang Yin et al. [11] numerically investigated effect of corrugated sinusoidal wavy channels for different phase shift between the upper and lower wavy plates having same equivalent diameter on heat transfer and fluid flow characteristics. The investigation has been carried out on uniform wall temperature condition for air (Pr = 0.696) having range of Reynolds number, $2000 \leqslant Re \leqslant 10000$. The results plotted for effect of phase shift and Reynolds number on heat transfer and fluid flow characteristics and relative thermal hydraulic performance enhancement was evaluated. The simulation results showed that the corrugated channels have a considerable change in enhancement in heat transfer accompanied by increased pressure loss penalty, and the effect of phase shift on the flow and heat transfer is more noticeable in higher value of Reynolds number region compared to lower Reynolds number region. Yasar Islamoglu and Cem Parmaksizoglu [12] has done experimental investigation to determine heat transfer coefficients in forced convection and friction factor for air flowing in corrugated channel employed in plate heat exchangers. Experiment have been carried out for two values of channel height as 5mm and 10mm for a single corrugation angle of 20^0 with Reynolds number varied from 1200 to 4000. It has been seen that, increase of channel height resulted in increased in the fully developed Nusselt number and the friction factor but performance considering flow area goodness factor slightly decreased. It has been found that with increase in the channel height, the pressure gradient decreases but the friction factors increase but the performance for a smaller channel height is relatively good.

Paisarn Naphon [13] numerically studied heat transfer enhancement and flow characteristics of in–phase corrugation having corrugated tilt angles 20^0, 40^0 and 60^0 with channel height 12.5mm. For solving the model, a finite volume method was used with the structured uniform grid system. The range of Reynolds number and heat flux having range of 400 – 1600 and 0.5 – 1.2kW/m^2 respectively. It has been observed that the net heat transfer rate from the wavy wall to the fluid increases due to higher temperature gradient near the corrugation wall as tilt angle increases. Also by decreasing the channel height, the turbulent intensity increases. At 60^0 wavy angle, higher fluid re–circulation occurs which provides larger surface area, therefore the Nusselt number also increases which resulted in heat transfer enhancement and pressure drop. J. Stasiek et al. [14] has experimentally investigated the effect of crossed–corrugated geometry on heat transfer enhancement and pressure drop. The experimental work done on sinusoidal wave having corrugation angle $\theta = 36^0$ and focus on local Nusselt number measured by true color digital processing of liquid crystal images. The relation between average Nusselt number on the corrugation angle θ for different values of Re and P/Hi (pitch of corrugation to internal height of corrugations) was studied and optimum design in rotary regenerators for conventional fuel power stations was investigated. It has been observed that average Nusselt number was found to increase approximately as $Re^{2/3}$ for all the cases investigated in this study. It was also seen that equivalent friction coefficient decreases with the Reynolds number roughly as $Re^{-1/2}$ and increases with P/Hi.

Hyun Goo Kwon et al. [15] investigated the effect of corrugation angles on two dimensional heat and mass transfer characteristics and flow features in a rectangular wavy duct. To simulate two dimensional characteristics, the corrugated test duct width was taken to be 7.3mm and aspect ratio of 7.3 with the corrugation angles used were 100^0, 115^0, 130^0, and 145^0. Numerical simulation was done using Ansys Fluent, to analyze the fluid flow and oil lamp black method was used for fluid flow visualization. Using a technique of naphthalene sublimation, local heat and mass transfer coefficients on the corrugated walls were measured. The Reynolds number was varied from 700 to 5,000 in this study. The numerical analysis and experimental results showed detailed features in the wavy duct. In this study, main flow impinged on upstream of a pressure wall and the flow prominently improved heat and mass transfer. Janusz Wojtkowiak and Lukasz Amanowicz [16] studied experimentally the influence of triangular corrugation shape on cooling capacity of ceiling panels having corrugation angle β ranging from 30° to 180° and corrugation length L was from 30mm to 120mm. The laboratory panel have width of 380mm and length of 1502mm with surface emissivity $\varepsilon = 0.9$. From experimental and theoretical result, it was observed that the cooling power of the corrugated surface increased by 15 to 20% compared to a traditional flat surface along with enhancement in appealing and operational features of the panel. The optimum parameters obtained at L = 40mm and β = 90°, which were 90% higher than the specific power of a reference panel with a flat surface and found for typical room conditions ($\varepsilon = 0.9$, $T_{air} = T_w = 25$ °C and $T_s = 18$°C), the cooling capacity of the panel with values L = 30mm and β = 30°, was 121 W/m^2 while for the panel of flat surface it is 61 W/m^2.

2.2 Effect of operating parameters

J. E. O'Brien and E. M. Sparrow [17] experimentally investigated heat–transfer coefficients in forced convection and friction factors for flow in a corrugated duct. The corrugation angle was taken to be 30^0 and the inter wall spacing was equal to the corrugation height. The Reynolds number, obtained from duct hydraulic diameter, ranges betwwen 1500 to 25,000, and the Prandtl number ranging from 4 to 8 were considered. Nusselt numbers correlated in the periodic fully developed regime, resulted in a Reynolds–number dependence of $Re^{0.614}$ and a Prandtl number dependence of $Pr^{0.34}$. The heat transfer enhancement as compared to a conventional parallel plate channel was about a factor of 2.5. Friction factors achieved from measured axial pressure distributions were virtually independent of the Reynolds number and equal to 0.57, a value appreciably greater than that for unidirectional duct flows. M. M. Ali & S. Ramadhyani [18] have experimentally investigated the convective heat transfer in the entrance region of corrugated channels with water as the working fluid and two channel spacing were studied for a corrugation angle of 20^0. The Reynolds number varied in the range of $150 \leqslant Re \leqslant 4000$. Flow visualization for low Reynolds number, flow conditions projected the presence of longitudinal vortices, whereas at higher Reynolds numbers, the existence of span wise vortices was clearly seen. For Reynolds number less than 1500, the Nusselt numbers in the corrugated channels exceeded those in the parallel plate channel by approximately by 140% and 240% for the two channel spacing's, whereas the corresponding increases in friction factor being 130% and 280%. M. Gradeck et al. [19] experimentally investigated heat transfer enhancement in a single phase flow and the effects of hydrodynamic conditions on it. In order to obtain the different regimes from steady laminar to turbulent, wide range of Reynolds numbers, ($0 < Re < 7500$) was used. A 2–D corrugated test section which has been instrumented with thermocouples can be heated by electrical cartridges. The local thermocouple was used to estimate the local and global heat transfer coefficient of the wavy heat exchanger. Because of the mixing induced by the recirculation in the wake of the corrugations, the heat transfer was found to be higher than those in rectangular channel. The measured temperatures along a corrugation was in a good agreement to the general structure of the fluid flow and very heterogeneous temperature distribution along the undulation was observed in case of forced convection.

Yan Cao et al. [20] studied effect of corrugation on flow and thermal characteristics of the upward non–boiling air/water two–phase flow. The heat transfer enhancement occurred due to recirculating flow formation in the cavities of the corrugated sections. For measuring the wall temperatures ten contact type thermocouples were used and located with equal distance of 16cm. The parameters were taken as a constant heat flux of 800W, air flow rate (1 to 5lit/min) and water flow rate (2 to 8lit/min). It was observed that the size of the bubbles in the corrugated tube was smaller than the in smooth tube which results fastest transition between flow patterns and enhanced thermal characteristics compared to that of the smooth tube. Also, the two–phase heat transfer coefficient increased with increment in the superficial gas Reynolds number and volumetric flow rate ratio. Paisarn Naphon [21] has presented the pressure drop and heat transfer characteristics in the channel with V corrugated lower and upper plates under constant heat flux. The experimental test section is the channel with two opposite corrugated plates on which all configuration peaks lie in a staggered arrangement. The testing is done for the corrugated plates with three different corrugated tile angles of 20^0, 40^0 and 60^0. The experimental has been carried out for Reynolds number ranging from 2000 – 9000 and heat flux ranging from 0.5 – 1.2kW/m^2. The effects of heat flux and the different geometrical parameters of the corrugated structure on the pressure drop and heat transfer characteristics were studied. It was seen that, because of the presence of recirculation zones, the heat transfer coefficients obtained from the channel with the corrugated surface are higher than those with the plain surface and the pressure drop also increases. S. Harikrishnan and Shaligram Tiwari [22] presented the study of three–dimensional numerical investigations on heat transfer and fluid flow characteristics of sinusoidal wavy channel with secondary corrugations. Considering different wave amplitudes and number of waves in streamwise as well as spanwise directions for fixed width and height of the channel, computations were carried out by using commercial software ANSYS Fluent 17.2. Heat transfer and fluid flow characteristics of secondary corrugated channels were compared with channels having spanwise and streamwise corrugations alone. With the help of streamline plots, flow characteristics were explained. To demonstrate the strength of secondary flow generated in different corrugated channels, volume weighted average values of secondary flow intensity have been shown. With the help of field synergy principle, effect of secondary flow on heat transfer characteristics has been explained.

Salman Al zahrani et al. [23] numerically investigated heat transfer characteristics for a sinusoidal corrugated plate heat exchanger having single (water – water) and two (air – water) phase flow using computational fluid dynamics (CFD). The chevron angle (β) was taken as 60^0 with Reynolds number ranging from 500 to 3000 and Prandtl number from 0.72 to 7.5. It was observed that with increment of Reynolds number and Prandtl number the Nusselt number value also increased which causes heat transfer enhancement. The inlet boundary condition was velocity inlet whereas outlet boundary condition was pressure outlet. The temperature of water was maintained at 18^0C. The first simulation was carried out for hot air and second for hot water. The results were expressed in the form of Nusselt number and isothermal fanning fraction as a function of heat transfer and pressure drop respectively which are nothing but non dimensional parameters. J.I. Corcoles Tendero et al. [24] numerically studied the effect of spirally corrugation on friction factor and heat transfer enhancement and compared with experimental data for validation. The parameters were taken as Reynolds number ranging from (15×10^3 to 40×10^3), Prandtl numbers (2.9 and 4.3), Inner diameter (18mm), Length (6m) with thickness 1mm of stainless steel tube. The corrugation depth was taken as 0.43mm with helical pitch of 15.86mm. The 3–D analysis was done using ANSYS Workbench (v.17.0) with a refined mesh property and k – epsilon ($k - \varepsilon$) turbulence model near the wall to confirm that the laminar viscous sublayer was captured. It was observed that 17% relative error for an average Nusselt number compared with the experimental data and 9% difference in the fanning factor.

2.3 Effect of nano - fluid

Raheem K et al. [25] studied numerically effect of semicircle, trapezoidal, and house shapes corrugation profiles on thermal performance with using nanoparticles volume fractions of ZnO (0 to 0.8) having Reynolds number ranging from 10,000 to 30,000. It was observed that there was decrement in thermal performance for house shaped (7.4%), trapezoidal (8.7%), and semicircle (4.86%) whereas increment in Nusselt number and pressure drop about 1 to 4 times. Also, channels with corrugation profile have 1.5 to 2.2 times thermal performance than that of flat corrugation estimated using performance evaluation criterion (PEC) and performance evaluation criterion was about 2.2 for trapezoidal channel at volume fraction 0.08 and Reynolds number of 10,000 which was superior than other corrugation profiles. Raheem K. Aieela et al. [26] analyzed thermal performance of different corrugated channels using nanofluids having structural shape semicircle corrugated channel (SCC), trapezoidal corrugated channel (TCC), and straight channel (SC) under constant heat flux and turbulent flow with 1% and 2% volume fraction of SiO_2–water and Al_2O_3–water nanofluids with a size of 20nm. It was observed that as volume fractions of nanofluids and Reynolds number increased, the heat transfer and pressure drop also augmented and a trapezoidal corrugated channel with $\phi = 2\%$ of silica nanofluid have greatest enhancement ratio along thermal performance of 1.94. The heat transfer enhancement occurs due to reduced cross section area of flow, reduced cross section area of flow and turbulent intensity. The impact of nanofluids was greater than impact of corrugation profile on heat transfer enhancement ratio which recorded as 11.75% and 10.5% at 2% volume fraction and Re = 10,000 for silica and alumina nanofluids, respectively.

Raheem K. Ajeel et al. [27] investigated experimentally the effect of semicircle–corrugated channel (SCC) and the trapezoidal–corrugated channel (TCC) using silicon dioxide (SiO_2) – water nanofluid as working fluid on heat transfer enhancement and compared with straight channel (SC) performance. The parameters were taken as Reynolds numbers ranging from 10,000 to 30,000 and nanofluid with SiO_2 volume fractions of 0.0%, 1.0%, and 2.0%. It was observed that SiO_2 – water nanofluid at 2.0% volume fraction provided improvement in heat transfer ratio around 9.6 – 10.15%. Also heat transfer augmentation rated up to 63.59% at trapezoidal–corrugated channel and thermal performance up to 2.22 times as compared to those of straight channel at Reynolds numbers 10,000 with volume fraction of 0.02. Dan Huang et al. [28] experimentally studied an effect of hybrid nanofluid mixture containing alumina nanoparticles with a volume concentration of 1.89% and multi–walled carbon nanotubes (MWCNTs) with a volume concentration of 0.0111% in a chevron corrugated–plate heat exchanger on heat transfer characteristics. It was observed that the hybrid nanofluid mixture increases the heat transfer coefficient as compared to Al_2O_3/water nanofluid due to addition of MWCNTs which increased the thermal conductivity of the mixture at a same flow velocity and pumping power. Hybrid nanofluid mixtures used in heat transfer applications since it have smaller pressure drop. Also the increase in heat transfer is within the error range since the hybrid nanofluid mixture was prepared by mixing the Al_2O_3/water nanofluid and MWCNT/water nanofluid and the mixture was not homogeneous nanocomposite.

M.A. Khairul et al. [29] analyzed the effects of water and CuO/water nanofluids in the corrugated plate heat exchanger on parameters like heat transfer coefficient, heat transfer rate, frictional loss, pressure drop, pumping power and exergy destruction. It was observed that the heat transfer coefficient was increased about 18.50 to 27.20% with CuO/water nanoparticles volume concentration from 0.50 to 1.50% compared to water. It was concluded that due to employment of nanoparticles and increment of particle volume fraction with its volume flow rate there was enhancement in friction factor which causes higher pressure drop and pumping power besides CuO/water nanofluids at 0.5%, 1.0% and 1.5 volume% increases the heat transfer coefficient about 17.70%, 21.80% and 24.7%, respectively and reduced the exergy destruction by 24%, 16.25% and 8% with compared to water. Vikas Kumar et al. [30] studied experimentally the effect of geometrical parameter (spacings X = 2.5mm, 5.0mm, 7.5mm and 10.0mm) using combined energetic and exergetic performance and various nanofluids, i.e., TiO_2, Al_2O_3, ZnO, CeO_2, hybrid ($Cu+Al_2O_3$), graphene nanoplate (GNP) and multi–walled carbon nanotube (MWCNT) in plate heat exchanger (PHE). It was observed that the MWCNT/water nanofluid, with a spacing of (X = 5mm) in PHE, has increment in pressure drop and extreme heat transfer coefficient, which was 53% greater compared to water at 0.75 volume % (optimum) along with enhanced exergetic performance. For TiO_2/water, Al_2O_3/water, ZnO/water, CeO_2/water, hybrid, GNP and MWCNT nanofluid the exergetic efficiency were founded as 7.56%,12.58%, 18.66%, 26.70%, 41.45%, 50.26% and 58.14% respectively, with respect to water for spacing (X = 5mm) at 0.75 volume% and hence concluded that among all tested nanofluids MWCNT was best coolant. Dan Amr Kaooda et al. [31] investigated thermal, hydraulic, and overall energy performances of nanofluid (distilled water "DW", GNP–SDBS/DW, Al2O3/DW, and SiO2/DW) flows in corrugated tubes having geometries (rectangular, triangular, trapezoidal, and curved ribs) using computational fluids dynamics (CFD) model and compared with DW flow in a smooth tube. It was observed that the overall performance enhancement was decreased at Reynolds numbers higher than 10,000 and the maximum overall performance improvement was about 37% for GNP–SDBS/DW nanofluid flow in a curvedly ribbed tube compared to DW flow. The heat transfer performance was improved about 20% using corrugated tube and 11% using nanofluids whereas it was enhanced up to 37% by combining both techniques and start falling performance at Reynolds number 10000.

3. Conclusion

The literature survey shows that the main resistance to heat transfer in conventional heat exchangers is the thermal conduction through the laminar sublayer attached to the surface. Enhancement of the heat transfer rate involves the elimination of this layer at the outflow of increased pressure drop. Treated surface is one of the most effective methods while designing the heat transfer devices as industrial purpose. In industries treated surfaces are mainly used in manufacturing of heat exchangers to increase heat transfer rate. The heat transfer rate is mainly depends upon temperature gradient, area of conductive barrier, heat flow rate of fluid and conductive flow. These factors are controlled by changing geometrical and operating parameters of the system or by introducing nano fluid to the base fluid. Among all the factors to control the area of barrier is the easiest and cost-effective method. Important engineering fields extensively use corrugated plate heat exchangers due to their simplicity in assembly/disassembly.

It was observed that compact surface is designed such that the thermos-hydraulic performance shows higher heat transfer rate and reduced pressure drop. One of the main problems still to overwhelm with compact surfaces is the boundaries they have in terms of the operating parameters that can withstand, since they cannot operate at high temperatures and pressures. Research and development in this area are focused in the development of new geometries and materials.

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