CHAPTER 2

REVIEW OF LITERATURE

This chapter discusses about the studies made on solar water heating system and various heat augmentation techniques addressed by the researchers.

2.1 INTRODUCTION

A flat plate collector is a large shallow box, typically mounted on a roof that heats the water using sun’s energy. It is the central component of the solar water heating system which converts solar energy into useful heat energy. Most of the previous research work has been focused on the performance improvement of collector area. In addition to that, the absorber plate efficiency, use of selective coatings, effect of absorber plate and its design, various thermal losses and effectiveness of insulation materials, effect of tilt angle, performance of different working fluids and characteristics of thermosyphon system have also been analyzed by many researchers and are elaborated under review of solar water heaters. Similarly, the effect of twisted tapes in heat exchangers, various twist geometries, working fluids, flow conditions and design of flow tubes are discussed under review on passive techniques.

2.2 STUDIES ON SOLAR WATER HEATERS

Generally, a solar water heater is characterized by its thermal performance and is influenced by the transmittance, absorption and conduction of solar energy and the conductivity of the working fluid. The absorber plate in a solar water heater plays a key role in the performance of
solar water heaters. Plate efficiency factor (F’) and heat removal factor (F_R) are the design parameters in the fabrication of solar collector systems. It has been analyzed by Hottle and Woertz (1942) and later redefined by Whiller (1953) and then by Hottle and Whiller (1958) which significantly reduced the empiricism associated in the design of solar collectors. Bliss (1959) proposed the mathematical derivations for various efficiency factors for different types of collectors, along with graphical data. Similarly, the collector efficiency and loss factors in solar air heaters have been analyzed mathematically by Parker (1981) and developed several equations to enable the designers to predict the collector performance for a selected flow rate and environmental conditions. Thermal performance of collector is also dependent upon the optical efficiency of glass cover, design and thermal properties of the absorber plate. The maximum energy conversion of absorber plate by the use of selective coatings that reduces the radiative losses has been analyzed by Stanley & Moore (1985), Cindrella (2007), Santamouris et al. (1990), Kalogirou et al. (2005) and Selvakumar et al (2012) . Roberts & Forbes (2012) developed expressions to compare selective absorbers with different absorptivity and emittance and to evaluate the effect of the above said parameters on the instantaneous efficiency of the collector system. The effect of thermal conductivity of the absorber plate has been studied through the Transient Simulation System by Shariah et al.(1999) which confirmed that the characteristic factors like fin efficiency factor, collector efficiency factor and heat removal factor are influenced by the thermal conductivity of absorber plate.

The thermal performance of solar water heater is subjective to the annular space between riser tube and absorber plate. This has been analyzed experimentally and theoretically by Bellow & Sambo (1992), Van Niekerk & Scheffler (1993), Adnan Sharia & Bam Shalabi (1997), Abdul Jabber Khalifa (1999) and Rakesh Kumar & Rosen (2010). Whiller and Saluja (1965)
analyzed the effect of contact between the riser tube and absorber plate and found that the efficiency factor ($F'$) of collector increases from 0.77 to 0.89 for soldered bond instead of unsoldered bond. The effect of various designs of absorber plate on the performance of a solar water heating system has been investigated in the due course. The use of artificial roughness on a surface to enhance the rate of heat transfer to fluid flow in the duct of a solar air heater has been analyzed by Mittal et al. (2007). Results show that the inclined ribs as roughness element exhibits effective efficiency that increases with increase in Reynolds number. The improvement in the thermal performance of solar water heater by corrugated absorber plate has been reported by Rakesh Kumar and Marc A. Rosen (2010). Results show that the thermal performance of corrugated solar water heaters depends significantly on the heat transfer rate between the absorber surface and water and on the amount of solar radiation incident on the absorber surface. In corrugated solar water, more solar energy is converted into useful heat but this modification reduces the efficiency of the system marginally. The use of Vee-shaped absorber plate to improve the convective heat transfer in the water heating system and solar air heaters has been analyzed by Joudi & Mohammed (1986), Abdul Malit et al. (2002), Varun et al (2007), Rajendra karwa & Girish (2013 and Saffa Fiffat & A Mayere (2013)

Further, the performance of solar collector depends significantly on the factors like geographical conditions, collector orientation, tilt angle and material of fabrication. Robel (1985), Andersen (1985) and Ali Anani et al.(1988) studied these aspects and reported the effect of these parameters on the thermal performance of the system. The external factors relating to geographical location and conditions can have greater impacts on the energy delivery of a solar energy system. It is generally associated with the sun’s available irradiance and spectral content, as well as a variety of environmental and climatic factors and is reviewed and reported by Travis Sarver et al.
The performance of solar systems (thermal or photovoltaic) is influenced by the ability of the glazing to transmit solar radiation to the collection surface, besides other factors, such as, incident radiation, tilt of collector, properties of materials, operating strategy, surroundings, etc. Also the accumulation of dust over the glass cover is the main obstruction in getting higher thermal performance of the collector. The influence of dust on the glazing used in solar air heaters with a plate tilt angle of 15°, exposure period of 30 days has been reported by Mastekbayeva and Kumar (2000). The results show that the fractional reduction in glass transmittance is around 75.8% and 87.9% and is dependent on dust deposition, climatic condition and tilt angle. The effect of dust accumulation in solar collectors with various tilt angles has been experimented by Soulayman (1991). Results show that 0° tilt angle is most contaminated with a mixture of coarse and fine dust particles and 90° tilt angle has slightest dust deposition.

Storage tank is an important component of the thermosyphon solar water heater system, because the thermal energy of the fluid which is absorbed in the riser tubes is stored in the storage tank. The effect of insulation thickness on the temperature profiles of the insulating material or lost by water has been investigated experimentally by Eldighidy (1991). Results show that the absorption coefficient decreases as the insulation thickness increases. Nwosu et.al (2013) developed a low cost fibre-reinforced plastic (FRP) hot water storage tank to provide a long term storage unit that efficiently retain and deliver stored hot water from solar collectors with minimal losses. Results show that ambient and geometric parameters as well as the tank insulation material properties can significantly impact the storage performance. The thermal behaviour of the stratified tank system when subject to constant temperature charging and constant volume hourly draws using TRNSYS simulation environment has been analysed by Dickinson et.al (2013). Further, experimental studies have been carried out by Glembin and
Rockendorf (2012) to investigate different discharging and charging strategies and their effects on the performance of a combined solar thermal system. Results show that a good thermal stratification within the storage lead to higher energy saving and it can be reached by both a stratified charging and discharging. This also reveal that depending upon the system size and the design of charging and discharging connections the stratified discharging leads to the same or even higher energy savings than a stratified charging. The thermosyphon solar water heaters works on the buoyancy force created in the storage tank is determined by the mass flow rate of collector loop. Numerous works on the performance of solar water heaters with various operating parameters throughout the day have been undertaken by Woodman (1977), Hossian et al (2011), Damir Dovic et al (2012), Cruz-Peragon et al (1968), Siddhartha et al (2012) and Yong Sin Kim et al (2013). The effect of mass flow rate that increases proportionate to the height between the collector and storage tank has been analyzed experimentally by Guptha and Garg (1968). Duffie and Beckman (1980) made several assumptions regarding mass flow rate of collector like neglecting the headers area, uniform distance between riser tubes, laminar flow and uniform distribution of flow in the tubes that proved to be useful for the design of thermosyphon system. Similarly, Parent et al. (1990) analyzed the use of natural convection heat exchangers in solar hot water systems to replace the pump on the tank side of the exchanger and presented two theoretical models for the exchanger to validate the experimental results with the theoretical model. Further, Huang (1993) developed a rating method for the thermal performance of thermosyphon solar water heaters based on Taiwan standard CNS B7277 which can be used to rate the thermal performance of different thermosyphon solar water heaters during the energy-collections period.

The economic viability in terms of its life cycle savings over a conventional water heating system using TRANSYS simulation program has
been investigated by Michaelides et al. (1992). Results show that the yearly solar contribution of the system ranges from 63% for a high hot water consumption profile to 89% for a low consumption pattern. Also the payback period of the system is as low as 3 years when compared to electric water heating systems and increases to 7-9 years when diesel oil is used and is depending on the hot water consumption profile used. Hussein et al. (1999) investigated the thermosyphon flat-plate solar collector under transient conditions and developed the governing equations of the different components of the collector in terms of dimensionless forms. In the same manner Chien et al. (2011) investigated a two-phase thermosyphon solar water heater at different solar radiation intensities and tilt angles and proposed two different methods for improving the performance of the collector. Results show that the best charge efficiency of the system is 82% which is higher than the conventional solar water heaters and the charge efficiencies increases up to 4%.

Amid the assorted factors, working fluid plays a significant lead in heat enhancement research, since the working fluid converts the solar energy in to thermal energy. The two phase closed thermosyphon (TPCT), called gravity heat pipe is one of the simplest configuration used in solar water heater system to augment the thermal energy from solar energy. Abou-Ziyan et al (2001), Venugopal et al. (2010), Ordaz-Flores et al. (2012), Leong et al. (2012), Long & Zhang (2013), Robert Macgregor et al. (2013), Yan-jun chen et al. (2013) and Long & Zhang (2013) incorporated a heat pipe in solar water heater and performed studies using various working fluids like water, nano fluids, refrigerants and alcohol. The thermal performance of a thermosyphon filled with R-134a has been analyzed by Ong et al. (2003). Results indicate that the heat flux transferred increased with increasing coolant mass flow rate, fill ratio and temperature difference between bath and condenser section. Further, the heat transfer behavior of a two phase thermosyphon in the
supercritical region using CO$_2$ as a working fluid has been investigated by Lin Chen et al. (2013a, 2013b). Results show that the natural circulation loop flow will change from unstable sub-critical two-phase flow to stable liquid flow, and then become stable super critical circulation with the increase of system initial pressure. Further, it was found that the two-phase flow or single phase flow at sub-critical region may lead to instability.

Numerous designs of solar collectors have been investigated to enlighten the thermal behavior of thermosyphon systems. A stationary V-trough solar water heating system with simulated solar concentration of 1.8 sun’s has been proposed by Chong et al. (2012). The use of stationary V-trough increases the optical efficiency up to 70.54%. This analysis is useful in the construction of low cost, efficient solar heating systems for domestic and commercial applications. Cost accounted for fabrication of solar water heater is a major feature in economic analysis. Bellamy (2012) carried out experimental measurements to assess the energy performance of a solar-heated stratified concrete wall panel which comprises an interior layer of high thermal mass concrete and an exterior layer of insulating concrete that is embedded with a solar thermal collector covering 10% of the panel’s face. Results indicate that the collector improves the energy performance of stratified concrete panels by more than 15%. This could be used by architects while designing the roof of the building which may serve as a low cost solar collector to provide hot water at moderate temperature for meeting various purposes during daytime.

2.3 STUDIES ON PASSIVE TECHNIQUES FOR HEAT TRANSFER ENHANCEMENT

The performance of collector can be improved; cost and size can be reduced by many heat transfer enhancement techniques. These techniques are broadly divided into active and passive method. Many researchers are
attracted towards passive technique of improving heat transfer rate such as a twisted tape insert since it does not need any external power. Chamoli et al. (2012) reported a review on various turbulence promoters used in solar heaters. A comprehensive review on various heat augmentation techniques used in the thermosyphon solar water heating systems has been reported by authors (2011). Comparing the active and passive techniques, the later is found to have better heat enhancement without the aid of any external energy. Amid various passive augmentation devices the use of twisted tapes are found to be effective in augmenting the convective heat transfer. Twisted tapes induce swirl flow and increase both heat transfer and pressure drop of the system. This has been analyzed by Saha et al. (1989), Kumar & Prasad (2000), Sha et al. (2001), Paisarn Naphon (2006), Shyy Woei Chang et al. (2007), Bharadwaj et al. (2009), Jaisankar et al. (2009), Wongcharee & Eiamsa-ard (2011), Suvanjan et al. (2013) and Si-hong Song et al. (2013). Alberto García et al. (2013) analyzed the use of wire-coil inserts to enhance the heat transfer in a typical flat plate solar water heater with optical efficiency of 77% and heat loss coefficient of 5.76 W/m²K at a rated mass flow rate of 0.04 kg/s. Results reveal that the wire-coil inserts promote an average increase in thermal efficiency from 14% to 31% and an increase in the useful power collected with no additional pressure losses of up to 8-12%, for the values of mass flow rates investigated. Sivashanmugam & Suresh (2006) investigated the heat transfer and friction factor characteristics of a circular tube fitted with full-length helical screw element of different twist ratio, increasing and decreasing order of twist ratio set with uniform heat flux and found that there is no much change in the magnitude of heat transfer coefficient enhancement with increasing twist ratio and with decreasing twist ratio set, as the magnitude of swirl generated at the inlet or at the outlet in the order of increasing twist ratio or decreasing twist ratio, is same in both the cases.
Yonghua You et al. (2012) investigated the thermo-hydraulic performance of laminar flow numerically and studied the effects of some geometrical parameters. Computation show that the average Nusselt number of enhanced tube is augmented by 3.7-5.51 times, while the average friction factor increases by 5.31 – 14.77 times those of plain tube. Numerical results indicate that larger strip size, smaller strip-wall gap and smaller strip pitch can effectively enhance the heat transfer rate, but also increase the flow resistance. The impact of slant angle depends on the magnitude of Reynolds number and also the Nusselt number and friction factor are sensitive to the geometry angle. Experimental investigation on heat transfer and friction factor characteristics of circular tube fitted with right-left helical screw inserts of equal length, and unequal length of different twist ratio, and the effect of right-left helical screw inserts on heat transfer and friction factor have been presented by Sivashanmugam & Nagarajan (2007). Results acknowledge that the heat transfer coefficient enhancement for right-left helical screw inserts is higher than that for straight helical twist for a given twist ratio. In the same way, Ibrahim (2011) studied the heat transfer and friction factor characteristics of a full length helical screw element of different twist ratio and helical screw inserts with different spacer length in a horizontal double pipe flat tube. The study confirms that the Nusselt number and friction factor decrease with the increase on pitch and twist ratio.

The consequence of heat transfer and friction factor characteristics of the tube containing extended surface on the inner wall and fitted with full length twisted tapes has been studied analytically by Liao and Xin (2000). The effect of coils and twisted tape in circular tube has been studied by Ujhidy (2003). The experimental results confirm that secondary flow is induced in the channel between the tube wall and the surface of helical element. The flow visualizing analysis and measurements using LDA technique indicate that the measured experimental data agree well with
numerical calculations. Modified Dean Number is proposed, which takes into account the curvature of the spherical line cut out by the helical element from the tubular housing.

Experimentation on heat transfer characteristics of circular tube fitted with straight full twist insert has been presented by Siva Rama Krishna et al. (2009). Experiments were carried out in turbulent flow using straight full twist insert with 2.4 inch spacer length. Results admit that there is no appreciable increase in heat transfer enhancement in straight full twist with 2 inch spacer and with 4 inch spacer, an increasing trend is observed in Nusselt number with Reynolds number. Halit Bas and Veysel Ozceyhan (2012) conducted similar type of experiments to investigate the flow friction and thermal behavior in a twisted tape which is inserted separately from the tube wall with twist ratios of 2, 2.5, 3, 3.5 and 4 and clearance ratios of 0.0178, 0.0357 under turbulent flow conditions, uniform heat flux. Results show that twisted tapes supplies considerable increase in heat transfer and pressure drop when compared with those from the plain tube. The Nusselt number and Reynolds number increases with the decrease of clearance ratio and twist ratio. For all investigated cases, heat transfer enhancement ($\zeta$) tends to decrease with the increase of Reynolds number and to be nearly uniform for Reynolds number over 15,000 and y/D lower than 3.0. The highest heat transfer enhancement is achieved as 1.756 for c/D = 0.0178 and y/D = 2 at Reynolds number of 5183. Consequently, the experimental results present that the best operating regime of all investigated twisted tape swirl generator inserts is detected at low Reynolds number, leading to more compact heat exchanger. Further, the heat transfer and pressure drop characteristics of horizontal pipe with twisted tape insert is investigated by Naphon (2008). Experimentation is carried out with aluminum twisted tape having thickness of 1 mm and a length 2000 mm. Cold and hot water are used as working fluids in shell side and tube side respectively. Mass flow rate ranging between
0.01 and 0.7 kg/s and between 0.04 and 0.08 kg/s respectively is used. Results for twisted tape inserts prove that the heat transfer is higher than in plain tube. Similarly, Mogaji et al. (2013) presents experimental results of heat transfer coefficient and pressure drop during two-phase flow of R134a in a horizontal tube containing twisted-tape inserts. The test section is a 2 m long copper tube of 15.9 mm inner diameter. The experiments were performed for tapes with twist ratios of 9 and 14 and a tube without insert. The mass velocity ranged from 75 to 200 kg m$^{-2}$ s$^{-1}$ and the vapor quality from 5 to 95%, for adiabatic condition and for constant heat flux of 10 kW m$^{-2}$. Results conclude that the use of twisted-tape inserts is suitable if applied to the high vapor quality region of the evaporator and under high mass velocities. Further Al-Fahed et al. (1998) carried out experiments to compare the pressure drop and heat transfer coefficients for a plain, microfin, and twisted-tape insert-tubes. The twisted-tape experiments include three different twist ratios each with two different widths. The data were taken at Reynolds numbers in the laminar region. The heat transfer data were obtained in a single shell-and-tube heat exchanger where steam is used as a heat source to obtain a uniform wall temperature and the working fluid in the tube is oil. The twist ratio and the width of the tape seem to have a large effect on the performance of the twisted-tape insert. Results demonstrate that as the twist ratio decreases, the twisted-tape will give better heat transfer enhancement. The loose-fit ($W=10.8$ mm) is recommended to be used in the design of heat exchanger where low twist ratios ($Y=5.4$, and $Y=3.6$) and high pressure drop situations are expected since it is easier to install and remove for cleaning purposes. Other than these situations, the tight-fit tape gives a better performance over the loose-fit tape. For the microfin tube, the data shows a small increase in both heat transfer and pressure drop. This type of microfin tube is not recommended to be used in laminar flow conditions.
Works involving improvement in design and geometry of twisted tapes for improving the heat transfer effect is numerous. In this regard, correlations were developed for predicting the heat transfer, friction factor and thermal enhancement efficiency through a circular tube fitted with triple twisted tape inserts in terms of twist ratio (Y), Reynolds number (Re) and Prandtl number (Pr) by Bhuiya et al.(2013). Investigations were conducted using the mild steel triple twisted tapes with four different twist ratios (Y = 1.92, 2.88, 4.81 and 6.79) for Reynolds number ranging from 7200 to 50,200 under uniform heat flux condition. The experimental results demonstrated that the Nusselt number, friction factor and thermal enhancement efficiency increased with decreasing twist ratio. The results indicate that, the presence of triple twisted tapes led to a higher increase in the heat transfer rate over the plain tube. The Nusselt number and friction factor of using the triple twisted tape inserts were found to be increase up to 3.85 and 4.2 times when compared with the plain tube. The heat transfer performance has been evaluated based on the constant blower power and the performance achieved is 1.44 by the use of triple twisted tape inserts. Similar configuration of helical screw twisted tape inserts has been analyzed for both laminar regime by Zhang et al.(2012) and Sivashanmugam & Suresh (2006). Helical screw tape with different twist ratios, increasing and decreasing order of twist has been considered in this study. Results show that heat enhancement is always higher in helical screw tape than the plain tube and there is not much change in magnitude of heat transfer coefficient enhancement while increasing (or) decreasing twist ratio. Empirical correlation developed for Nusselt number and friction factor are fitted with experimental data within the range of ± 15% and ± 13% respectively. The maximum heat enhancement and performance ratio of 2.05 has been obtained for the minimum twist ratio 1.95. Isothermal pressure drop tests and heat transfer experiments under uniform heat flux conditions have been carried out by Alberto García et al.(2007) for tubes fitted with twisted tape and wire coil insert. The experimental study was on three wire coils of
different pitch inserted in a smooth tube in laminar and transition regimes. The friction factor increases and lie between 5% and 40% in the fully laminar region. The transition from laminar flow to turbulent flow is continuous, without the instabilities and the pressure drop fluctuations that a smooth tube presents. Heat transfer experiments have been performed in the flow ranges: $Re=10$–2500 and $Pr = 200$–400. At Reynolds numbers below 200, wire coils do not enhance heat transfer with respect to a smooth tube. For Reynolds numbers between 200 and 1000, wire coils remarkably increase heat transfer. At Reynolds numbers above $Re \approx 1000$–1300, transition from laminar to turbulent flow takes place. At Reynolds number around 1000, wire inserts increase the heat transfer coefficient up to eight times with respect to the smooth tube. A performance comparison between wire coils and twisted tape inserts has shown that wire inserts perform better than twisted tapes in the low Reynolds number range: $Re = 700$–2500.

The effect of tube geometry on the heat transfer area has been studied by many researchers. Flow pattern and thermal-hydraulic characteristics in an innovative tube insert have been experimentally and numerically investigated by Solano et al. (2011). The insert device is a concept envisioned for reciprocating scraped surface heat exchangers. It consists of a concentric rod, on which is mounted on an array of semi-circular plugs fitted to the inner tube wall. In motionless conditions, the insert works as a turbulence promoter, enhancing heat transfer in laminar regime. Fundamental flow features in the symmetry plane of the tube have been assessed with Particle Image Velocimetry technique. A general model of the flow mechanism has been defined, which allows the identification of three regions along a geometrical pitch: recirculation bubbles, flow acceleration and transverse vortex. Results have been complemented with experimental data on pressure drop and heat transfer. CFD simulations for different Reynolds numbers provide a further insight into the relation of the flow structures with wall shear stress, and their
role in the local heat transfer augmentation. Numerical and experimental analyses were carried out by Yu-Wei Chiu and Jiin-Yuh Jang (2009) to study thermal–hydraulic characteristics of air flow inside a circular tube with different tube inserts. Three kinds of tube inserts, including longitudinal strip inserts (both with and without holes) and twisted-tape inserts with three different twisted angles ($\alpha = 15.3^\circ$, $24.4^\circ$ and $34.3^\circ$) have been investigated for different inlet frontal velocity ranging from 3 to 18 m/s. Numerical simulation was performed by a 3D turbulence analysis of the heat transfer and fluid flow. The experiments were conducted in a shell and tube exchanger with overall counter flow arrangement. The working fluid in the tube side was cold air, while the hot Dowtherm fluid was on the shell side. To obtain the heat transfer characteristics of the test section from the experimental data, the $\varepsilon$-NTU (effectiveness-number of transfer unit) method is applied to determine the overall conductance (UA product) in the analysis. It was found that the heat transfer coefficient and the pressure drop in the tubes with the longitudinal strip inserts (without hole) were 7–16% and 100–170% greater than those of plain tubes without inserts. When the longitudinal strip inserts with holes were used, the heat transfer coefficient and the pressure drop were 13–28% and 140–220%, respectively, higher than those of plain tubes. The heat transfer coefficient and the pressure drop of the tubes with twisted-tape inserts were 13–61% and 150–370%, respectively, higher than those of plain tubes. Furthermore, it was found that the reduction ratio in the heat transfer area of the tube of approximately 18–28% may be obtained if the twisted-tape tube inserts are used. Swirl generators inserted into a conventional smooth tube is an innovative way to increase the thermal performance of the heat exchangers. The effect of the free rotation of a swirl device on the thermal performance and friction behaviors has been investigated experimentally by Weerapun Duangthongsuk & Somchai Wongwises (2013). Five turbine-type swirl generators with and without free rotation are inserted and installed equally distant along the test section. The data for a common smooth tube are
compared with the data for fixed (FTSG) and freely rotating turbine type swirl generator (RTSG). The measured data illustrate that the heat transfer performance of the tube with RTSG inserts is 6.3% and 56% higher than that of the FTSG insert and the conventional smooth tube, respectively. Moreover, the heat transfer coefficient significantly increases when the fluid flow pass the RTSG and FTSG inserts. However, inserting the RTSG and FTSG into the common smooth tube resulted in an increase of the pressure drop. The tube with RTSG inserts gives the lowest pressure drop. The effect of conical ring in laminar flow induced heat transfer and pressure drop due to vibration has also been studied by Promvonge (2008), Anvari et al. (2011) and Aiwu Fan et al. (2011).

Smith Eiamsa-ard and Pongjet Promvonge (2010) investigated the effect of twisted tape with serrated-edge insert on heat transfer and pressure loss behaviors in a constant heat-fluxed tube. The serrated twisted tape (STT) was inserted into the entire test tube with a constant twist ratio in order to generate a continuous swirling airflow. Two geometry parameters of the STT has been considered in the work are the serration width ratio and the serration depth ratio. The measurements have been conducted for the airflow rate based on Reynolds numbers in the turbulent regime from 4000 to 20,000. The experimental results of the STT inserted tube are compared with those of the plain tube fitted with typical twisted tape (TT). The results show that the heat transfer rate in terms of Nusselt number, Nu increases with the rise in the depth ratio but decreases with increase in the width ratio. The heat transfer rate is up to 72.2% and 27% relative to the plain tube and the TT inserted tube, respectively. The use of the STT leads to higher heat transfer rate and friction factor than that of the TT for all cases. The thermal performance factor of the STT tube under constant pumping power was evaluated and found to be above unity indicating that using the STT tube is advantageous over the TT tube or the plain tube. Further, the circular tube is modified as a
square duct in which the experimentation is carried out with twisted tape inserts by Ray and Date (2001). The transport equations are solved by using pressure correlation algorithms. Heat transfer characteristics are predicted under axial and peripheral constant wall heat flux conditions. Relative thermo-hydraulic performance of square duct is found to be significant than circular tube with twisted tape. Results reveal that increase in heat transfer in square tube is considerably higher (up to a maximum of 350%) than circular tubes, both fitted with tapes of same twist ratio, for fluids with higher Prandtl number. While the studies involving twisted tapes are in progress, the modeling of the phenomena through numerical methods is carried out by many researchers. The modeled parameters are validated with experimental results.

Aside from the helical twisted tape, helical screw tape, helical twisted tape with conical ring, micro-fin, serrated tape and coils, a variety of geometry of twisted tapes has been developed and used to blend the fluid particles titled as kenics static mixer. Modeling of two-phase liquid–liquid flows and particle history was analyzed in terms of the residence time through a Kenics static mixer by means of computational fluid dynamics (CFD) by Jaworski and Pianko-Oprych (2002). The two modeled phases were assumed viscous and Newtonian with the physical properties mimicking an aqueous solution in the continuous and oil in the dispersed (secondary) phase. Three levels of superficial flow velocity were chosen to result in Reynolds numbers ($Re$) equal to 100, 200 and 400, respectively. The numerical simulations were performed with the help of the commercial software Fluent™, version 5.4.8. The modeling involved both block-structured grids and fully non-structured grids for a static mixer with 10 Kenics inserts. Each of the two grid types had three density levels. The algebraic slip mixture (ASM) model was used in the Eulerian frame of reference and enabled the prediction of the pressure drop across the inserts, the local velocities and volume fraction of the two phases.
The Lagrangian approach was used to track the trajectory of dispersed fluid elements (drops) in the simulated static mixer. Mixing efficiencies and energy requirements of various motionless mixer designs for laminar mixing applications has been presented by Heywood et al.(1984). The effectiveness of five designs of motionless mixer for laminar mixing has been assessed using an autocorrelation technique for mixture quality assessment based on colour development of two streams of epoxy resin, one colored black, the other white. The performance of the mixers was assessed by referring improvement in mixture quality to the power consumption required by each mixer design. The results show that although the Ross ‘ISG’ unit gave the most rapid mixing in terms of the number of elements required, or the length of mixer, to give a specified improvement in mixture quality, the power requirement incurred was extremely high. The largest improvement in mixing quality per unit power consumption was obtained using the Kenics ‘Static Mixer’ and the Ross ‘LPD’ design, with the Sulzer Brothers' ‘SMX’ and ‘SMV’ designs ranked between the Ross ‘LPD’ and ‘ISG’ mixers. The analysis of residence time in kenics static mixer is performed by Kenan Yarkut et al.(2004), Jarjan Rafiee et al.(2011) and Yonghua You et al.(2012).

A method based on computational fluid dynamics (CFD) for the characterization of static mixers using the Z factor, helicity and the rate of striation thinning has been presented by Regner et al.(2006). These measures were found to be well-suited for the characterization of static mixers as they reflect the pressure drop, the formation of secondary flow, i.e. vortices, and their effect on the mixing process. In the mixers investigated, secondary flow is formed in the flow at the element intersections and due to the curvature of the mixer elements. The intensity of the vortices is higher in the Lightnin than the Kenics mixer due to edges in the middle of the Lightnin mixer elements. The formation of vortices affects the Zfactor by an increase in the power requirement, and the rate of striation thinning by an increase in the stretching of the striations. The formation of vortices was observed at a Reynolds
number of 10 in both mixers with aspect ratios of 1.5. However, the intensity of the vortices was greater in the Lightnin than the Kenics mixer, which was observed in not only the magnitude of the helicity, but also the Z factor, rate of striation thinning and the distribution of striation thickness. The distribution in striation thickness is shifted towards thin striations as the flow rate is increased from below to above the Reynolds numbers of which vortices were first observed, but some striations still pass the mixer elements almost unaffected, which can be seen in the skewness of the distribution of the striation thickness, which shifts from being negative to positive. The performance of industrially relevant static mixers that work via chaotic advection in the Stokes regime for highly viscous fluids, flowing at low Reynolds numbers, like the Kenics, the Ross Low-Pressure Drop (LPD) and Low-Low-Pressure Drop (LLPD), the standard Sulzer SMX, and the recently developed new design series of the SMX, denoted as SMX(n) (n, Np, Ns) = (n, 2n − 1, 3n), is compared by Meijer et al. (2012) using criteria of energy consumption, measured in terms of the dimensionless pressure drop, and compactness, measured as the dimensionless length. Results show that open mixers are most energy efficient; giving the lowest pressure drop, but this goes at the cost of length, while the most compact mixers require large pressure gradients to drive the flow. In compactness, the new series SMX(n), like the SMX(n = 3) (3, 5, 9) design, outperform all other devices with at least a factor 2.

Further, heat transfer enhancement in a tube using twisted tapes with alternate axes at different alternate lengths (in term of alternate length to twist length ratio, l/y = 0.5, 1.0, 1.5 and 2.0) has been investigated by Eiamsa-ard et al. [120]. The twisted tapes with both uniform and non-uniform alternate lengths (TAs and N-TAs) as well as a typical twisted tape (TT) were comparatively tested for turbulent flow regime. The experimental results revealed that all the TAs and N-TAs yielded higher Nusselt number and
friction factor than the TT and the Nusselt number and friction factor obtained considerably increased with decreasing the alternate length ($l$). Heat transfer and friction factor by the N-TAs were found to be directly dependent of alternate length rather than the variation of the length. Similarly the effect of right-left helices has been studied by Smith Eiamsa-ard & Pngjet (2010), Hejazi et al.(2010), Govarthan & Sivahanmugham (2010) and Nanan et al.(2013). The heat transfer and friction factor characteristics of double pipe heat exchanger fitted with clockwise and counter clockwise arrangement of twisted tape is analyzed experimentally by Silapakij wongkul et al. (2006). Experiments are conducted for twist ratio of 0.4, 0.6 and 0.8 with Reynolds number varied from 2200 to 11500. The increased heat transfer rate for Clockwise-Counter clockwise and helical twisted tape are found to be 219% and 204% when compared with the plain tube. The increased friction factor for the same is around 4.7 and 1.5 times higher than the plain one.

Twisted tapes are used not only in heat exchanger, but also in solar water heater to improve the convective heat transfer. A heat transfer study of a solar collector with inserts differs from that of an ordinary heat exchanger analysis in the following ways.

i. In heat exchanger heat input is given by a heater and the heat flux can be maintained constant.

ii. The mass flow rate through the collector is directly proportional to the solar radiation. But in heat exchanger it can be controlled and maintained constant.

iii. The experimentation on solar collectors can be carried out only in open atmosphere whereas for heat exchangers, it is can be indoor. It has been experimentally verified for the first time by Kumar & Prasad (2000) in forced circulation mode. Experiments were carried out for various mass flow rates and twist ratio. Heat transfer and pressure drop in twisted tape collectors have been found to increase by 18–70%, and 87–132%, as
compared to plain tube collectors. Empirical correlations were developed for Nusselt number and friction factor and are fitted with experimental data. Results indicate that twisted tape collectors are preferable for higher grade energy collection and increase in the thermal performance and is around 30% more compared to the plain one. The performance of twisted tape collectors is found to be remarkable at higher values of solar radiation. Further experimentation on thermosyphon solar water heaters using twisted tape inserts for heat augmentation have been carried out by Jaisankar et al. (2009, 2011). The above studies have been carried out in series flow pattern in the solar collector. They also confirm that compared to series flow pattern, parallel flow has a better performance with improved thermal efficiency (2009).

2.4 BOUNDARIES OF THE EXISTING RESEARCH AND RESEARCH OPENING

Twisted tape is mainly used as an efficient passive technique to augment convective heat transfer in tube flow. So far, this technology has been adopted extensively in heat exchangers but their applications in solar water heaters are found to be limited. The heat transfer and friction factor characteristic of thermosyphon solar water heater has been analyzed only for very few designs of twisted tape geometries. Moreover it is also understood that twisted tapes with different geometries offer different performances and mechanisms of heat augmentation and flow pressure drop.

Helical, Left-Right and Kenics twisted tapes of various designs are already experimented both in heat exchangers and solar collectors. But the combination of above twist designs with rod and spacer of equal length has never been tested in a solar collector. Customized design of twist is developed
as a contribution of knowledge with a view of maximizing the thermal performance and minimizing the flow friction in the solar collector

- From the application point of view, solar water heaters work under both natural and forced circulation mode. From the utilization point of view, thermosyphon solar water heaters are popular due to ease of operation, low maintenance and initial cost. Research on heat augmentation is mainly focused on heat exchangers not on solar collectors.

- Most of research works cited in the literature referred to series flow operation and experimentation on parallel flow operation is limited.

- Only very few geometries of twisted tapes has been experimented in thermosyphon solar water heater out of numerous designs of twists which are tested in heat exchanges.

- Researches cited in the literature experimented with full length twists for heat augmentation. The use of full length twist not only augments the heat transfer but also the flow pressure drop. This could be minimized by using rod and spacers.

- The heat loss due to flow of air flowing over the glass cover of the solar collector has never been taken in to account. Since the solar collectors are placed in outdoor conditions the local air velocity plays a significant role in heat augmentation. By deflecting the air away from the surface of the collector, the efficiency can be improved.
2.5 COMMITMENT OF CURRENT RESEARCH

Present research is made to confirm the chattels of the above said constraints and to overcome the research gap by the following

- Analyze the performance of a parallel flow pattern collector and compare its thermal efficiency with the literature work.
- Compare the effect of full length helical twisted tapes over the helical twists regularly spaced with rod and spacer and analyze the heat transfer, friction factor and thermal performance.
- Compare the effect of full length Left-Right twisted tapes over the Left-Right twists regularly spaced with rod and spacer and analyze the heat transfer, friction factor and thermal performance.
- Compare the effect of full length Kenics over the Kenics twists regularly spaced with rod and spacer and analyze the heat transfer, friction factor and thermal performance.
- Compare the effect of full length customized twist (combination of helical, Left-Right and Kenics) over the customized twists regularly spaced with rod and spacer and analyze the heat transfer, friction factor and thermal performance.

2.6 CONTRIBUTION TO KNOWLEDGE

The following are the conclusions made related to the twist ratio based on the literature on heat exchangers and solar collectors.

i. Most of literature report the performance of twist inserted system with a minimum twist ratio 3 and maximum of 6.
ii. The thermal performance and Nusselt Number of the twist inserted systems found to decrease with increase in twist ratio. Based on this, twist with twist ratio of 3 offered the maximum thermal performance and it decreases with increase in twist ratio.

Reducing the twist ratio below 3 increases flow friction and decrease the mass flow rate; when the twist ratio is increased above 6, poor particle swirl and lower convective heat transfer is observed. Hence, the twist ratio for the present analysis is taken as 3 with an objective of minimizing flow friction without compromising the thermal performance by using different twist designs and by using rod and spacer of different length.

- To the author’s knowledge, studies on the effect of heat transfer and friction factor in thermosyphon solar water heating system using the above mentioned twisted tapes is the first of its kind.

- Analysis of the heat transfer and friction factor behavior of solar water heater in different phases such as Phase 1 and Phase 2.

- Correlations for heat transfer and friction factor for both phases are developed.

- Uncertainty analysis for heat transfer, friction factor and thermal performance has to be done to ascertain the error inclusion in the findings.

- Analyze the heat flow mechanism using simulation through commercial CFD (Fluent) software.