CHAPTER 2
LITERATURE SURVEY

2.1 INTRODUCTION

The available literature is briefly reviewed here to understand the effects of heat transfer and flow characteristics of heat exchangers in general and spiral heat exchangers in particular. The overview of the past, important research works relevant to this research are reviewed in this Chapter in four broad categories as listed below:

- Heat Exchangers
  - Geometries other than Spiral Configuration (16 references)
  - Spiral Geometry (23 references)
- Response Surface Methodology (17 references)
- Numerical Analysis and CFD Modelling (26 references)
- Intelligent modeling (36 references)

2.2 HEAT EXCHANGERS

2.2.1 Geometries other than Spiral Configuration

Kubair and Kuloor (1966) studied the pressure drop and heat transfer for laminar flow of glycerol for different types of coiled pipes, including helical and spiral configurations. Reynolds numbers were in the range of 80 to 6000 with curvature ratios in the range of 1/10.3 to 1/27. The number of turns ranged from 7 to 12. To provide constant temperature wall condition, a steam bath was used on the outside of the coil. The authors also noted that the results of the interaction between the heat transfer rates and the Graetz number were opposite to those of Seban and McLaughlin (1963). The authors speculated that this difference might have been due to the fact that the two studies used different boundary conditions, one being constant wall temperature and the other at constant heat flux. The results of Kubair and Kuloor (1966) coincided with those of Seban and McLaughlin (1963) at low Graetz numbers, but deviated at higher Graetz numbers.

Garimella et al. (1988) presented the average heat transfer coefficients of laminar and transition flows for forced convection heat transfer in coiled annular ducts. Two
different coil diameters and two annulus radius ratios of test sections were used in their experiments. They found that the heat transfer coefficients obtained from the coiled annular ducts were higher than those obtained from a straight annulus, especially in the laminar region.

Rabin and Korin (1996) developed a new simplified mathematical model for the thermal analysis of a helical heat exchanger for long-term ground thermal energy storage in soil for use in arid zones. The results obtained by solving a finite difference method were validated by experimental data.

Bolinder and Sunden (1996) solved the Navier–Stokes and energy equations by using a finite-volume method. The steady, fully developed, laminar, forced convective heat transfer in helical square ducts for various Dean and Prandtl numbers were analysed. The mean Nusselt number and the local peripheral variation of the Nusselt numbers were presented for Prandtl numbers ranging between 0.005 and 500. In addition, the correlations for the Nusselt number were proposed.

Cengiz et. al. (1997) studied the heat transfer and pressure drop in a heat exchanger constructed by placing spring shaped wire with varying pitch. The results indicated that the Nusselt number increased with decreasing pitch/wire diameter ratio on the basis of the experimental data for both empty helical pipes and helical pipes with springs installed inside.

Lin and Ebadian (1997) applied the standard k-ε model to investigate the three-dimensional turbulent developing convective heat transfer in helical pipes with finite pitches. The effects of pitch, curvature ratio and Reynolds number on the developments of the effective thermal conductivity and temperature fields, local and average Nusselt numbers were discussed. The results obtained from the model were in good agreement with the existing experimental data.

Xin et. al. (1997) studied the effects of coil geometries and the flow rates of air and water on pressure drop in both annular vertical and horizontal helicoidal pipes. The test sections with three different diameters of inner and outer tubes were tested. The results showed that the transition from laminar to turbulent flow covered a wide Reynolds number range. On the basis of the experimental data, a correlation of the friction factor was developed.
Li et al. (1998 and 1999) applied the renormalisation group model for considering the three-dimensional turbulent mixed convective heat transfer in the entrance region of a curved pipe (1998). The relative magnitude of buoyancy and centrifugal effects on the secondary flow was characterised by using a new proposed dimensionless parameter. Comparison between the results obtained from the model and experiments showed good agreement. In addition, they numerically studied the developing turbulent flow and heat transfer characteristics of water near the critical point (1999). Based on the constant wall temperature with and without buoyancy effect, the velocity, temperature, heat transfer coefficient, friction factor distribution and effective viscosity were presented and discussed.

Lin and Ebadian (1999) presented the effects of inlet turbulence level on the development of three dimensional turbulent flow and heat transfer in the entrance region of a helically coiled pipe for constant wall temperature and uniform inlet conditions. The Control-Volume Finite Element Method with an unstructured, non-uniform grid system was used to solve the governing equations. The results showed that at distances far from the entrance, the inlet turbulence level did not affect the bulk turbulent kinetic energy. The influence of the turbulence level on the development of the friction factor and Nusselt number was significant only for a short axial distance from the entrance.

The various parametric studies such as thermal properties of the soil, cycle period, and height and pitch of the helical coil heat exchanger were studied by Zheng et. al. (2000). They applied a control-volume finite difference method having second-order accuracy to solve the three-dimensional governing equations. The laminar forced convection and thermal radiation in a participating medium inside a helical pipe were analysed. By comparing the numerical analysis, including and not including thermal radiation, the effects of thermal radiation on the convective heat transfer were investigated. They found that the thermal radiation could enhance the total heat transfer rate.

Rennie and Raghavan (2002) simulated the heat transfer characteristics in a two-turn tube in-tube helical coil heat exchanger. Various tube-to-tube ratios and Dean Numbers for laminar flow in both annulus and in-tube were examined. The temperature profiles were predicted using a computational fluid dynamics package
Pheonics 3.3. The results showed that the flow in the inner tube at the high tube-to-tube ratios was the limiting factor for the overall heat transfer coefficient. This dependency was reduced at the smaller tube to tube ratio, where the influence of the annulus flow was increased. In all the cases, as other parameters were kept constant, increasing either the tube Dean Numbers or annulus Dean Numbers resulted in an increase in the overall heat transfer coefficient.

Yang and Chiang (2002) studied the effects of the Dean number, Prandtl number, Reynolds number and the curvature ratio of the heat transfer for periodically varying curvature curved-pipe inside a larger diameter straight pipe to form a double-pipe heat exchanger. The results showed that the heat transfer rate was increased by up to 100% as compared with a straight pipe. All of the experimental data were regressed to obtain the correlation of the Nusselt number.

2.2.2 Spiral Geometry

Lamb B.R. (1982) reported that plate and spiral heat exchangers provided an excellent means of achieving highly efficient heat recovery because of their high heat transfer coefficients coupled with counter flow arrangements. Lamb reported from industrial examples, out of his experience, in applying heat recovery as an integral part of industrial processes. He also concluded that based on the practical situations, the plate and spiral heat exchangers were proved to be a low cost route to heat recovery.

Martin (1992) numerically studied about the heat transfer and pressure drop characteristics of a spiral plate heat exchanger. The apparatus used in the investigations had a cross section of $5 \times 300 \text{ mm}^2$, number of turns $n=8.5$, core diameter of 250 mm, outer diameter of 495 mm and $5 \times 5$ cylindrical bolts in a rectangular in line arrangement of $61 \times 50 \text{ mm}$. He also presented empirical correlations for heat transfer and friction factor that cover a wide range of Reynolds numbers for their particular set up with water as a medium.

Bes T.H. and Roetzel W. (1993) analytically investigated the heat transfer in a counter flow spiral heat exchanger. They conducted a thermal analysis on the basis of the energy balance equations and developed an universal formula to calculate the mean temperature difference correction factor $F$ for a spiral plate heat exchanger.
They proposed a dimensionless criterion number CN which could be recognized as the criterion number for the spiral heat exchanger. Their approach allowed the testification process such that the approximate theory fitted with the exact theory and the new theory appeared to be useful for the design of counter flow spiral heat exchanger.

Ho J.C.et. al. (1994) developed two theoretical models to predict the performance of a compact heat exchanger based on unmixed and mixed air flow considerations. The experimental results based on a laboratory model agreed well with the predicted performance of the theoretical models.

Ho J.C. and Wijeysundera (1996) developed a theoretical model to predict the thermal performance of the spiral-coil heat exchanger as a cooling and dehumidifying unit. They conducted laboratory experiments and the results confirmed the theoretical predictions.

Wijeysundera N.E. et. al. (1996 a) developed an expression for the effectiveness of a spiral coil heat exchanger. They conducted an experimental study to measure the effectiveness in a closed loop test set-up. They concluded that the computed effectiveness agreed well with the measured values.

Wijeysundera N.E. et. al. (1996 b) developed a model of spiral coil heat exchanger (SCHE) operating as a cooling and dehumidifying unit based on a mixed-air flow configuration and a Lewis number equal to one. They have developed performance curves for the SCHE unit to relate the enthalpy and the humidity effectiveness to the NTU. Experiments conducted on a laboratory model of the SCHE confirmed very well with the theoretical predictions.

Wang R.Z.(1997) proposed spiral plate heat exchangers as adsorbers. They developed a prototype heat regenerative adsorption refrigerator using the activated carbon-methanol pair and tested. They found that the adsorption system using 12 kg activated carbon has a cycle time of 40 minutes and 14 kg ice per day was made. The expected ice making power density would be 2 to 4 kg ice per kg adsorbent per day after further improvement.

Ho J.C. and Wijeysundera N.E. (1999) developed a theoretical model based on the assumption that the air was unmixed as it flowed past each spiral coil turn.
Experiments on a laboratory model of the spiral coil unit were conducted and the results obtained confirmed the theoretical predictions.

Yang Dong et. al. (2001) carried out an experimental study to determine the turbulent friction and heat transfer characteristics of four spirally corrugated tubes, which had various geometrical parameters, with water and oil as the working fluids. Experiments were conducted and the results showed that the thermal performance of these tubes was superior compared to a smooth tube, but the heat transfer enhancements were not as large as the friction factor increases. The enhanced tubes showed an enhancement in tube-side heat transfer coefficients ranging from 30% to 120% and friction factor enhancement of 60 to 160% compared to smooth tubes.

An average in-tube heat transfer coefficient in a spirally coiled tube was proposed by Naphon and Wongwises (2002). The test section was a spirally coiled heat exchanger consisting of six layers of concentric spirally coiled tubes. The experiments were performed under cooling and dehumidifying conditions and considered the effects of inlet conditions of both working fluids on the in-tube heat transfer coefficient. The results obtained from the experiments were compared with those calculated from other correlations. A new correlation for the in-tube heat transfer coefficient for spirally coiled tube was proposed.

In their second and third papers, Naphon and Wongwises (2003a and 2003b) developed a mathematical model to determine the performance and heat transfer characteristics of spirally coiled finned tube heat exchangers under wet-surface conditions. In addition, the heat transfer characteristics and performance of a spirally coiled heat exchanger under dry surface conditions were studied theoretically and experimentally. The calculated and measured results were in reasonable agreement.

Bengt O.Neeraas et. al. (2004) constructed a test plant for the measurements of local heat transfer coefficients and frictional pressure drops on the shell side of spiral-wound LNG heat exchangers. Measurements were performed with single phase vapour flow, liquid film flow and two phase shear flow. A total number of 171 liquid falling film heat transfer measurements were performed with ethane, propane, methane/ethane mixture, ethane/propane mixtures and ethane/n-butane mixture as test fluids. The calculated values were compared to measured values.
Naphon and Wongwises (2005) experimentally investigated the average tube-side and air-side heat transfer coefficients in a spirally coiled finned tube heat exchanger under dry and wet-surface conditions. The test section was a spiral-coil heat exchanger, which consisted of six layers of concentric spirally coiled tube. The chilled water and the hot air were used as the working fluids. The effects of the inlet conditions of both working fluids flowing through the heat exchanger on the heat transfer coefficients were discussed. New correlations based on the data gathered during their work for predicting the tube-side and air-side heat transfer coefficients for the spirally coiled finned tube heat exchanger were proposed.

Nuntaphan et al. (2005a) studied a total of 23 cross-flow heat exchangers having crimped spiral configurations. The effect of tube diameter, fin spacing, transverse tube pitch and tube arrangements were examined. For the inline arrangement, the pressure drop increased with the rise of tube diameter, but the associated heat transfer coefficient decreased with it. The increase of fin height also gave rise to considerable increase of pressure drop and decrease of heat transfer coefficients for the inline arrangement. However, for the staggered arrangement, the effect of the fin height on the pressure drop was much smaller than that of the inline arrangement due to the major contribution to the total pressure drops from the blockage of the airflow from staggered arrangement. The effect of the fin spacing on the air side performance was strongly related to the transverse tube pitch for both inline and staggered arrangements. Correlations of the present crimped spiral fins in both staggered and inline arrangements were developed. The proposed correlations gave fairly good predictive ability against their present test data.

Nuntaphan et al. (2005b) experimentally examined the air-side performance of a total of 10 cross flow heat exchangers having crimped spiral configurations under the dehumidification. The effect of tube diameter, fin spacing, fin height, transverse tube pitch and tube arrangements were examined. The results indicated that the heat transfer coefficient of wet surface was slightly lower than that of dry surface. The effect of tube diameter on the air-side performance was significant. Larger tube diameter not only gave rise to lower the heat transfer coefficient, but also contributed significantly to the increase of pressure drops. This phenomenon was applied in both dry and wet conditions. For wet surface, the influence of fin height was negligible and
the effect of fin spacing on the heat transfer performance was rather small. However, increasing the fin spacing decreased the heat transfer coefficient. The tube arrangement was found to play an important role on the heat transfer coefficient, narrower transverse pitch gave higher heat transfer coefficient. The proposed correlations could predict 95% of experimental data within 15% accuracy.

Paisarn Naphon and Somchai Wongwises (2005) studied the heat transfer characteristics and the performance of a spiral coil heat exchanger under cooling and dehumidifying conditions. The heat exchanger consisted of a steel shell and a spirally coiled tube unit. The spiral-coil unit consisted of six layers of concentric spirally coiled tubes. Each tube was fabricated by bending a 9.27 mm diameter straight copper tube into a spiral-coil of five turns. Air and water were used as working fluids. The chilled water entering the outermost turn flowed along the spirally coiled tube, and flowed out at the innermost turn. The hot air entered the heat exchanger at the centre of the shell and flowed radially across spiral tubes to the periphery. A mathematical model based on the mass and energy conservation was developed and solved by using the Newton–Raphson iterative method to determine the heat transfer characteristics. The results obtained from the model were in reasonable agreement with the experimental data. The effects of various inlet conditions of working fluids flowing through the spiral coil heat exchanger were discussed.

Nuntaphan. A and Kiatsiriroat .T (2007) investigated the effect of fly-ash deposit on the thermal performance of a cross-flow heat exchanger having a set of spiral finned-tubes as a heat transfer surface. A stream of warm air having high content of fly-ash was exchanging heat with a cool water stream in the tubes. In their study, the temperature of the heat exchanger surface was lower than the dew point temperature of air, thus there was condensation of moisture in the air stream on the heat exchanger surface. The affecting parameters such as the fin spacing, the air mass flow rate, the fly-ash mass flow rate and the inlet temperature of warm air were varied while the volume flow rate and the inlet temperature of the cold water stream were kept constant at 10 l/min and 5 °C, respectively. From the experiment, it was found that as the testing period was shorter than 8 hours, the thermal resistance due to the fouling increased with time. Moreover, the deposit of fly-ash on the heat transfer surface was directly proportional to the dust–air ratio and the amount of condensate on a heat
exchange surface. However, the deposit of fly-ash was inversely proportional to the fin spacing. The empirical model for evaluating the thermal resistance was also developed. The simulated results agreed well with those of the measured data.

Picon-Nunez M. et. al. (2007) presented a shortcut method for the sizing of spiral plate heat exchangers. The approach consisted of an iterative process where the physical dimensions like plate width and external spiral diameter were given initial values. Convergence was achieved until the calculated pressure drop and heat duty met the required specifications of the design problem. The results of the application of the approach were compared with case studies reported in the literature. A numerical study using computational fluid dynamics was performed to rate the performance of the geometry. The analytically calculated temperature profiles of the exchanger showed the same tendency as those obtained numerically. Thus, the method provided a good starting point for estimating the dimensions of spiral heat exchangers in single-phase applications.

Rajavel R and Saravanan K (2008a) investigated the heat transfer characteristics of water-water system in a spiral plate heat exchanger. Experiments were conducted by varying the mass flow rate, temperature and pressure of the fluids. The effects of relevant parameters on spiral plate heat exchanger were investigated. The data obtained from the experimentation was compared with the theoretical data. A new correlation of the Nusselt number was proposed.

Rajavel R and Saravanan K (2008b) investigated the convective heat transfer characteristics of electrolytes. Experiments were conducted by varying the mass flow rate, temperature and pressure of cold fluid by keeping the mass flow rate of the hot fluid as constant. The effects of relevant parameters on spiral heat exchanger were investigated. The data obtained from the experimentation was compared with the theoretical data. A new correlation of the Nusselt number was proposed.

However, the performance analysis of Spiral plate Heat Exchanger (SHE) using RSM optimisation, CFD modelling and Intelligent modelling are not much reported in the literature. Hence an attempt is made in this work, to study the performance analysis based on the above said techniques.
2.3 RESPONSE SURFACE METHODOLOGY

Seung-Jae Moon (2006) numerically examined the heat and flow characteristics of a single-phase parallel-flow heat exchanger to obtain its optimal shape. A response surface methodology was introduced to predict the performance of the heat exchanger with respect to selected design parameters over the design domain. The design parameters were the inflow and outflow angles of the working fluid and the horizontal and vertical locations of the inlet and outlet. The relative priority of the design parameters was evaluated to identify the most important parameters and these were then optimised using response surface methodology. The JF factor was chosen as the evaluation, characteristic value since it could consider the heat transfer and pressure drop simultaneously. The JF factor of the optimum model was 5.3% greater than that of the reference model.

Aslan N. and Cebeci Y. (2007), proposed to apply Box–Behnken experimental design and response surface methodology for modelling of some Turkish coals. The Box–Behnken experimental design was used to provide data for modelling and the variables of the model were the bond work index, grinding time and ball diameter of the mill. Coal grinding tests were performed by changing these three variables for three size fractions of coals. Using these sets of experimental data obtained by mathematical software package (MATLAB 7.1), mathematical models were then developed to show the effect of each parameter and their interactions. Predicted values obtained using model equations were in good agreement with the experimental values. Their study proved that Box–Behnken design and response surface methodology could efficiently be applied for modelling of grinding of some Turkish coals.

Sarkar Mannan et. al. (2007) investigated and optimised the process parameters for the bioconversion of activated sludge by *Penicillium corylophilum* using response surface methodology (RSM). The three parameters, namely temperature of 33°C, agitation of 150 RPM, and pH of 5 were chosen as a center point from the previous study of fungal treatment. The experimental data on chemical oxygen demand (COD) removal (%) were fitted into a quadratic polynomial model using multiple regression analysis. The optimum process conditions were determined by analysing the response surface three-dimensional surface plot and contour plot and by solving the regression
model equation with the Design Expert software. Box-Behnken design technique under RSM was used to optimise their interactions, which showed that an incubation temperature of 32.5°C, agitation of 105 RPM, and pH of 5.5 were the best conditions. Under these conditions, the maximum predicted yield of COD removal was 98.43%. These optimum conditions were used to evaluate the trail experiment and the maximum yield of COD removal was recorded at 98.5%.

Wan-Qian Guo et. al. (2009) attempted to design an optimum and cost-efficient medium for high-level production of hydrogen by Ethanoligenens harbinense B49 by using response surface methodology (RSM). Based on the Plackett-Burman design, Fe$^{2+}$ and Mg$^{2+}$ were selected as the most critical nutrient salts. Subsequently, the optimum combination of the selected factors and the sole carbon source, glucose were investigated by the Box-Behnken design. Results showed that the maximum hydrogen yield of 2.21 mol/mol glucose was predicted when the concentrations of glucose, Fe$^{2+}$ and Mg$^{2+}$ were 14.57 g/L, 177.28 mg/L and 691.98 mg/L, respectively. The results were further verified by triplicate experiments. The batch reactors were operated under an optimised condition of the respective glucose, Fe$^{2+}$ and Mg$^{2+}$ concentration of 14.5 g/L, 180 mg/L and 690 mg/L, the initial pH of 6.0 and an experimental temperature of 35 ± 1°C. Without further pH adjustment, the maximum hydrogen yield of 2.20 mol/mol glucose was obtained based on the optimised medium with further verified the practicability of this optimal strategy.

Karin Kandananond (2010) determined the optimal cutting conditions for surface roughness in a turning process. The process was performed in the final assembly department at a manufacturing company that supplies, fluid dynamic bearing (FDB) spindle motors for hard disk drives (HDDs). The work pieces used were the sleeves of FDB motors made of ferritic stainless steel, grade AISI 12L14. The optimised settings of key machining factors, depth of cut, spindle speed, and feed rate on the surface roughness of the sleeve were determined using the response surface methodology (RSM). The results indicated that the surface roughness was minimised when the depth of cut was set to the lowest level, while the spindle speed and feed rate were set to the highest levels. The methodology deployed could be readily applied to different turning processes.
Balayanan et. al. (2011) et. al. carried out experimental and theoretical research to investigate the thermal performance of a water to air thermosyphon heat pipe heat exchanger. Many factors were seemed to affect the thermal performance of the heat pipe heat exchanger including heat input, water temperature and velocity of output air, filling ratio of the working fluid and pipe material. Out of those independently controllable process parameters, heat input, water temperature and air velocity were selected as factors to carry out the experimental work. The experiments were conducted based on three factor five level central composite rotatable designs with full replication technique. A correlation was developed for the effectiveness of heat pipe heat exchanger in terms of heat input, water temperature and velocity of air. The developed mathematical model was helpful in analysing the performance of heat pipe heat exchanger.

Vahid Khalajzadeh and Ghassem Heidarinejad (2011) carried out a three dimensional computational fluid dynamics simulation based on the effective parameters on the heat exchanger efficiency and the total heat transfer efficiency in cooling mode and with the aid of the second-order Response Surface Model. Two functions for the total heat transfer efficiency and the heat exchanger efficiency were derived. The effects of different design parameters on the response variables were examined. Based on the Response Surface Model, it was found that the dimensionless inlet fluid temperature and the dimensionless pipe diameter significantly affect the response variables, while the response variables were weakly affected by dimensionless depth. Finally, an optimisation was performed and the optimum heat exchanger is defined using the model equations.

Amenaghawon N.A. et. al. (2013) optimised the citric acid production from hydrolysed corn starch. Response surface methodology (RSM) was employed for the analysis of the simultaneous effect of substrate concentration, broth pH and fermentation temperature on the concentration of citric acid produced during fermentation of hydrolysed corn starch. A three-variable, three-level Box-Behnken design (BBD) comprising of 15 experimental runs was used to develop a second degree statistical model for the optimisation of the fermentation conditions. The optimal fermentation conditions that resulted in the maximum citric acid concentration were substrate concentration; 50 g/L, broth pH; 2.00 and fermentation
temperature; 25°C. Under these conditions, the concentration of citric acid was obtained to be 31.96 g/L. Validation of the model indicated no difference between predicted and observed values.

Anurag kumara et. al. (2013) devised an innovative approach to predict the rate of heat transfer of a wire-on-tube type heat exchanger by utilising the support vector machine model. To solve this algorithm, a computer program was developed using MATLAB software. This helped them to formulate an equation for the total heat transfer, which gave minimal error when compared to traditional techniques. This model exhibited inherent advantages due to its use of the structural risk minimisation principle in formulating cost functions and of quadratic programming during model optimisation. A comparative study between the artificial neural network and the support vector machine approach was also illustrated. They concluded that Genetic Algorithms were an effective and powerful tool in optimisation.

Debasmit N.and Rajasimman M.(2013) carried out research on the degradation of atrazine in batch reactors using mixed micro organisms obtained from pharmaceutical wastewater sludge. The effects of process parameters like pH, temperature, inoculum concentration, and agitation speed on atrazine degradation were studied and optimised using response surface methodology (RSM). The optimum condition for the maximum degradation of atrazine was pH – 6.7, temperature – 29.3 °C, inoculum concentration – 5%, and agitation speed – 137 RPM. In these conditions, the effect of tyrosine concentration was studied. From the results, it was found that increase in atrazine concentration decreased the degradation efficiency. The maximum atrazine degradation was found to be 94.4%. Various cell growth models and substrate inhibition models were used to describe the atrazine degradation kinetics. From the results, it was found that Haldane model fits the data well with $R^2$ value of 0.9001.

Dilipkumar et. al. (2013) carried out research on the production of inulinase in a packed bed reactor (PBR) under solid state fermentation. The parameters like air flow rate, packing density and particle size were optimised using response surface methodology (RSM) to maximise the inulinase production. The optimum conditions for the maximum inulinase production were: air flow rate - 0.82 L/min, packing density - 40 g/L and particle size - 0.0044 mm (mesh - 14/20). In these optimised
conditions, the production of inulinase was found to be 300.5 unit/gram of dry substrate (U/gds).

Ho-Seung Jeong and Jong-Rae Cho (2013) proposed and optimised a new heat exchanger tube shape by reducing the size of the tube bundle and improving structural characteristics such as the thermal stress and resonance. Various tube shapes were proposed and a FE analysis was performed to select the tube with the best structural characteristics. The response surface methodology was employed to establish mathematical approximation models using the results of design of experiments as a function of the geometric parameters of the selected tube. Also, the main effects of various geometric parameters of the selected tube were investigated. The geometric parameters such as offset length, the straight distance between one end and the other end of the tube, the tube length in a straight portion and fillet radius were assessed. The geometric parameters of the selected tube were optimised using the RSM and multi-objective genetic algorithm. They suggested the calculated coefficients of the regression equation for the objective function, optimised data, and an optimisation procedure of the tube. The presented findings could be used in the preliminary design of the heat exchanger used in high temperature.

Manohar M. et. al. (2013) used the Box Behnken design approach for planning the experiments for turning Inconel 718 alloy with an overall objective of optimising the process to yield higher metal removal, better surface quality and lower cutting forces. Response Surface methodology (RSM) was adopted to express the output parameters (responses) that were decided by the input process parameters. RSM also quantified the relationship between the variable input parameters and the corresponding output parameters. RSM designs allowed them to estimate interaction and even the quadratic effects, and hence, gave them an idea of the shape of the response surface. The model was validated by performing experiments, taking three sets of random input values. The output parameters measured through experiments (actual) were in a good match with the predicted values using the model. Using ‘Design Expert’ software, 2D and 3D plots were generated for the RSM evolved.

Sathiyan Selvakumar et. al. (2013) carried out an experimental study on the treatment of textile dye wastewater in a batch reactor using *Ganoderma lucidum*. The characteristics of textile dye wastewater were studied. The effect of process
parameters like pH, temperature, agitation speed and dye wastewater concentration on dye decolourization and degradation were studied. These parameters were optimised using response surface methodology (RSM). From the results, the optimised conditions were: pH 6.6, temperature 26.5 °C, agitation speed 200 RPM and dye wastewater concentration 1:2. In these optimised conditions, the maximum decolourisation and COD reduction were found to be 81.4 and 90.3 %. Kinetic studies were carried out using different models like first-order, diffusional and Singh model. From the results, it was found that the degradation follows the first-order reaction model.

Lei Sun and Chun-Lu Zhang (2014) proposed a numerical model to simultaneously predict the fluid flow and heat transfer on both air-side and water-side of elliptical FTHE. The numerical results agreed well with the reported experimental data. Response surface methodology was applied to understand the interactions among seven design factors, including the number of rows, axis ratio, transversal tube pitch, longitudinal tube pitch, fin pitch, air velocity, water volumetric flow rate. Response surface analysis was used to evaluate the axis ratio effect on the overall thermal–hydraulic performance, which was quantified by the heat transfer rate per unit power consumption. The results indicated that the axis ratio strongly interacted with air velocity and water volumetric flow rate. The increase of the axis ratio improved the overall thermal–hydraulic performance at higher air velocity or lower water volumetric flow rate, but the opposite effect was observed at a lower air velocity or higher water volumetric flow rate.

Salam K.K. et. al. (2014) investigated the influence of operating parameters on the weight of wax deposit in oil-pipeline. Response surface methodology (RSM) was used to develop polynomial regression models and to investigate the effect of the changes in the level of wax temperature differential, flow rate and residence time on weight of wax deposit using Box Behnken design. The contribution of flow rate, time, square of significant to the model developed temperature, square of time and interaction between flow rate and time were investigated. It was observed that the experimental data fitted better because of the Predicted R² of 0.9618 was in reasonable agreement with the Adjusted R² of 0.9945. The agreement between the predicted and experimental values described the accuracy of the model developed and
could be used to navigate within the design space. The minimum value of wax deposit of 0.0195075 was achieved at temperature, flow rate and residence time values as 53.25°C, 499.54 ml/min and 3.01min respectively.

In this work, the experiments are planned based on the Box-Behnken design in order to minimise the number of experiments to save the time and resources (Design Expert software). If the experimental results of the overall heat transfer coefficient and pumping power show significant variation, then the experimental conditions need to be optimised in order to achieve the maximum possible overall heat transfer coefficient with the consumption of minimum pumping power (MINITAB). The experimentation and optimisation are planned to be carried out for all the six fluid systems in a spiral plate heat exchanger.

2.4 NUMERICAL ANALYSIS AND CFD MODELLING

Numerical studies have been performed in the past two decades on the flow and heat transfer characteristics of heat exchangers. Only a few numerical studies were reported in the literature on spiral plate heat exchanger for process fluids. Hence, a systematic work has been undertaken to study the numerical heat transfer and flow characteristics of spiral plate heat exchanger for few process fluids.

Numerical studies of laminar flow were performed by Truesdell and Adler (1970) using a square mesh. They found that the numerical procedure was used for Dean numbers up to 200. A further increase in the Dean number caused divergence of values resulting from their solution method. Helical coils with both circular and elliptical cross sections were used. The numerical procedure was based on circular and elliptical geometry. Results were compared with experimental results from the literature.

Numerical studies by Joseph et. al. (1975a) were carried out on the laminar flow with Dean numbers ranging from 0.8 to 307.8. Their results for Dean numbers less than 100 showed two secondary flow vortices similar to that found with circular cross sections. However, when the Dean number was increased above 100, four vortices were present; they confirmed these vortices with experimental flow visualisation experiments. These studies were further carried out to include oscillation of the coils.
Joseph et. al. (1975b). They found that if the oscillations were strong enough, then the secondary flow would reverse the direction.

Patankar and Prakash (1981) presented a numerical analysis for the flow and heat transfer in an interrupted plate passage, which was an idealisation of an offset fin heat exchanger channel, and compared the overall results with the available experimental data. Their calculation method was based on the periodically fully developed flow through one periodic module, and the effect of plate thickness in the offset strip fins was studied. They also assumed stable laminar wake and used a constant heat flux boundary condition with the additional specification that each row of fins were at a fixed temperature. Their calculations have shown that by varying the fin thickness at fixed Reynolds number based on the hydraulic diameter, the flow pattern changes, resulting in the overall heat transfer and friction loss. It was observed that only when the plate is sufficiently thick, the recirculation zones extend to the next plate. From their investigations, it was concluded that a thick-plate situation leads to significantly higher pressure drop, while the heat transfer does not sufficiently improve, despite the increased surface area and increased mean velocity.

Prusa and Yao (1982) considered the combined effects of both buoyancy and centrifugal forces on the flow field and temperature distribution in a hydro dynamically and thermally fully developed flow for horizontal heated curved tubes. The numerical results indicated that the mass flow rate was drastically reduced because of the secondary flow. Higher curved tube and overheating conditions lead to a decrease of the total heat transfer rate. A flow-regime map comprised of the dominant centrifugal force region, the dominant buoyancy and centrifugal forces region, and the dominant buoyancy force region, was presented.

Taylor dispersion in a curved tube was studied using both Monte Carlo and numerical techniques by Johnson and Kamm (1986). They examined the effects of secondary flow on axial dispersion for Dean numbers between 0 and 13, for curvature ratios less than 1:50, and for Schmidt numbers between 1 and 1000.

Tinaut et. al. (1992) developed a prediction model for a water/engine oil compact heat exchanger, which predicted the heat exchanger performance and effects on
various geometric parameters. Globally the expressions proposed were found to be acceptable when comparing the results of the model to the experimental data.

Wang and Andrews (1995) numerically studied the laminar flow of an incompressible fluid in a duct with rectangular cross section. Their work was to establish the effects of pitch ratio, pressure gradient, and curvature ratio on the fluid velocity distribution and the fluid resistance for fully developed flow using a finite difference method. They concluded that the pitch ratio affected the pattern of the secondary flow and the friction factor. As the pitch ratio was increased, the two-vortex flow developed into a single vortex flow. Friction factor was mainly affected by the curvature ratio of rectangular helical duct flow.

Manglik and Bergles (1995) studied 18 offset strip fin surfaces and analysed the effect of the non-dimensional parameters on them, and arrived upon a correlation to describe all three regions. They reanalysed all other different thermal hydraulic relationships and identified the asymptotic behaviour in the laminar and turbulent regimes.

Bolinder and Sunden (1996) solved the Navier-Stokes and energy equations by using a finite-volume method. The steady, fully developed, laminar, forced convective heat transfer in helical square ducts for various Dean and Prandtl numbers were analysed. The mean Nusselt number and the local peripheral variation of the Nusselt numbers were presented for Prandtl numbers ranging between 0.005 and 500. In addition, correlations for the Nusselt number were proposed.

Zhang et. al. (1997) investigated the heat transfer mechanism for both the inline and a staggered array of strip fins. Finite fin thickness was assumed and correlations for the transition region were derived from different Reynolds number values. They studied the time-dependent flow behaviour due to vortex shedding by solving two-dimensional and three-dimensional unsteady equations. The effect of vortices on the local Nusselt number and the overall heat transfer is studied.

Huttl and Friedrich (2000) applied the second order accurate finite volume method for solving the incompressible Navier–Stokes equations to study the effects of curvature and torsion on turbulent flow in helically coiled pipes. The incompressible Navier–stokes equations were expressed in an orthogonal helical
coordinate system. The results showed that the flow quantities were affected by the pipe curvature. Although the torsion effect was less, it could not be neglected. This was because it affected the secondary flow induced by pure curvature and resulted in an increase of fluctuating kinetic energy and dissipation rate.

Huttel and Friedrich (2001) used direct numerical simulation for turbulent flow in straight, curved and helically coiled pipes in order to determine the effects of curvature and torsion on the flow patterns. They showed that turbulent fluctuations were reduced in curved pipes compared to the straight pipes. They also demonstrated that the effect of torsion on the axial velocity was much lower than the curvature effect.

Hlide Van Der Vyver et. al. (2003) numerically developed a three dimensional CFD model for a tube-in-tube heat exchanger in which hot water was flowing in the inner tube and cold water was flowing in the outer tube. The CFD model was compared with empirical relations. The results showed reasonable agreement with the empirical relations. Also, the CFD results were compared with the values obtained from an independent experimental study. The experimental results showed good agreement with CFD calculations. They concluded that CFD could model a prototype heat exchanger accurately and could be used to determine the characteristics of a new design of heat exchanger.

Egner and Burmeister (2005) did a numerical study of spiral ducts of rectangular section using computational fluid dynamics techniques and determined the Nusselt number as a function of the Dean number, showing the strong dependence of the heat transfer coefficient upon the spiral radii. They demonstrated that, except for the entry regions, the heat transfer coefficient was nearly constant, however, at entry regions, heat transfer coefficients may be even as 50% larger than the fully developed values. An important contribution of their work was the general conclusion for estimating the thermal entry length for laminar Reynolds numbers between 100 and 500.

Jayakumar J.S., et. al. (2008) observed that the use of constant values for the thermal and transport properties of the heat transport medium resulted in the prediction of inaccurate heat transfer coefficients. They decided to incorporate conjugate boundary conditions instead of arbitrary boundary conditions. They fabricated an experimental setup to study the fluid-fluid heat transfer in a helically
coiled heat exchanger. They conducted experiments to find out the heat transfer coefficients. The CFD predictions made by them using FLUENT matched reasonably well with the experimental results. Based on the results a correlation was developed to calculate the inner heat transfer coefficient of the helical coil.

Conte I. and Peng X.F. (2009) conducted both numerical and experimental investigations to understand the convective heat transfer from a single round pipe coiled in a rectangular pattern. The studied heat exchangers were composed with inner and outer coils so that the exterior flow was very similar to the flow within the tube-bundles. The inner and outer coils of the heat exchangers were composed of bends and straight portions. The results showed that the staggered geometric arrangement gave better performance due to the tortuous flow characteristics and better mixing of the exterior fluid. The numerical and experimental results qualitatively agreed well with each other.

Khaled Saleh et. al. (2012) compared the different multi objective optimisation approaches that could be used to optimise the design of thermal equipment. Plate heat exchanger was taken as a case study to apply different optimisation techniques. The thermal-hydrodynamic characteristics of single phase turbulent flow in chevron-type plate heat exchangers with sinusoidal-shaped corrugations was studied. The computational domain contained a corrugation channel and the simulations adopted the shear-stress transport (SST) $k$-$\varepsilon$ model as the turbulence model. Two different approximations assisted optimisation approaches were tested. Offline approximation assisted optimisation, and online approximation assisted optimisation were compared to optimise plate heat exchanger design. For both the approximation techniques (offline and online), design optimisation was performed using a multi objective genetic algorithm based on meta-models that were built to represent the entire design space. In off-line approximation, globally accurate meta-models were built which required adding more samples. However, in online approximation assisted optimisation, samples were added just to improve the metamodels performance in the expected optimum region. Approximated optimum designs were validated using computationally expensive actual CFD simulations. Finally, a comparison between offline and online approximation assisted optimisation was presented with guidelines to apply both approaches in the area of heat exchanger design optimisation. The
methods presented in the paper could be applied to optimise different types of heat exchangers, electronic cooling devices and other thermal system components.

Martin Martinez Garcia and Miguel Angel Moreles (2012) considered the steady state heat transfer equations associated with two fluids in a spiral heat exchanger. They proposed a numerical method for solution to approximate the temperature distribution and overall heat transfer coefficients. Their method was tested and validated on two actual spiral heat exchangers that were reported in the literature.

Yoo Guen - Jong et. al. (2012) performed the numerical analysis to investigate the flow and heat transfer characteristics in a spiral coiled tube heat exchanger. The radius of curvature of the spiral coiled tube was gradually increased as the total rotating angle reached $12\pi$. As the varying radius of curvature became a dominant flow parameter, three dimensional flow analysis was performed to that flow together with different Reynolds numbers while constant wall flux condition was set in the thermal field. They found that the centrifugal force due to the curvature effect was found to have a significant role in the behaviour of pressure drop and heat transfer. The centrifugal force enhanced the pressure drop and heat transfer in spiral coiled tubes than those of a straight tube.

Abo Elazm M.M., et. al. (2013) studied the effects of changing the taper angle on the heat transfer characteristics of a helical coil by using FLUENT software for investigation. They found that the Nusselt number increased with increasing taper angle. A MATLAB code was built based on empirical correlation of Manlapaz and Churchill for ordinary helical coils. The CFD simulation results were found acceptable when compared with the MATLAB results.

Brahim Selma et. al. (2013) developed an optimised heat pipe heat exchanger which was used to improve the energy efficiency in building ventilation systems. The optimised design was based on a validated numerical model used inside a numerical plan built on a design of experiments statistical procedure. The numerical model was validated through experimental measurements done on a small scale heat pipe industrial exchanger. Modelling results showed good agreement with experimental measurement thus proving the model’s potential as a tool in heat pipe engineering design.
Karnav N Shah et. al. (2013) reported the analysis of pressure drop and heat transfer characteristics over a staggered tube bank heat exchanger with different tube bundle arrangements using Fluent software. The model was set up with different mass flow rates. In order to improve the hydraulic and thermal performance of the heat exchanger, simulations were performed for 30°, 45° and 60° angle arrangements. They observed that there existed a good agreement for the pressure drop between simulation and correlation for 45° angle arrangement compared to the 60° angle arrangement whereas the pressure drop obtained in 60° was less compared to the 45° angle arrangement.

Xing Lu et. al. (2013) conducted an experimental investigation on the flow and heat transfer performance on the shell side of a spiral-wound heat exchanger. In terms of data reduction, the CFD results proved that the linear assumption of the air temperature changing along the axial direction was reasonable. They found that the CFD gave visualised images of the flow and heat fields. The experimental data showed that the heat transfer performance in multilayers was better than that in monolayers. They obtained the empirical relations for Nusselt number and friction coefficient.

Sousa J. et. al. (2014) proposed the experimental and numerical methodology to model the thermal performance of a surface cooler within an aero-engine. Experiments were carried out to determine the surface temperature distribution with infrared thermography. The thermal convective process was characterised by means of an ad-hoc three dimensional inverse heat conduction approach. An unprecedented energy model was then developed to analyse the sensitivity of the heat exchanger’s capacity to different engine operating conditions. The results indicated that the investigated concept may provide up to 76% of the estimated lubrication, cooling requirements during take-off of a modern gas turbine power plant.

Hence in this study, a numerical analysis of a spiral plate heat exchanger is planned to be carried out. The three dimensional model of the spiral plate heat exchanger is to be created in GAMBIT 2.4 software. The model is planned to be imported to FLUENT software for analysis for all the fluid systems incorporating the same experimental conditions proposed by the Response Surface Methodology
(RSM) based Box-Behnken design. The model validation will be carried out by comparing the CFD model outputs with those of the experimental conditions.

2.5 INTELLIGENT MODELLING

A model is a simpler analog of a physical process, which is developed to gain insight into the operation and ensures the accurate prediction of the parameters being modelled. Many researchers have applied empirical models in the given physical process. In spite of being simple and giving a reasonable fitting of the experimental data, these empirical models are capable of predicting data within the applied process conditions.

Intelligent models such as Artificial Neural Network (ANN), Adaptive Network based Fuzzy Inference System (ANFIS) and Gustafson-Kessel (G-K) fuzzy clustering can be employed to overcome this limitation.

The power of ANN lies in its ability to represent both the linear and non-linear relationships between inputs and outputs and in its capability to learn these relationships directly from the modelled data without any knowledge about the physics of the phenomenon of the process.

2.5.1 ANN Modelling

In recent years, many authors have utilised ANN to predict the performances of different types of heat exchangers (Mandavgane and Pandharipande 2006a and b, Thirumarimurugan et.al. 2011, Anurag Kurma et.al.2013 and Sivaraman 2014). In a Spiral plate Heat Exchanger (SHE), the author found only countable number of literatures reporting about ANN modelling (Thirumarimurugan et.al, 2011). In this reference, the ANN model was developed to study the performance of a SHE.

A survey of identification and control of dynamical systems using Neural Networks has been reported by Narendra and Parthesarathy (1990), Chen and Billings (1992), Hernandez and Arkun (1992), Hunt et.al. (1992) and Hussian (1999).

Mandavgane S.A. and Pandharipande S.L.(2006a) considered parameters like inlet and outlet temperatures of shell and tube side fluids and their flow rates for developing a model for heat exchangers. Artificial Neural Networks (ANN) were found to be effective in modelling of non-linear multi variable relationships and also
referred as black box models. For modelling of shell and tube heat exchanger, ANN architecture was optimised. The optimised ANN architecture was employed for water-20% glycerin and water-40% glycerin systems for the estimation of the exit temperature of both the fluids as a function of inlet temperature conditions and also flow rates. It was observed that the ANN model with three hidden layers (4-15-15-15-2) had a good level of accuracy (98-99.5%) for predicting values of training and test data set.

Mandavgane S.A. and Pandharipande S.L.(2006b) considered the concentration of flowing fluids as one of the variable parameters for heat exchanger modeling. They used different fluids viz.water, 20% glycerin and 40% glycerine. They developed a heat exchanger model using optimised ANN architecture. ANN is trained for water-water and water-40% glycerine and the trained network was used for the prediction of shell and tube side exit temperatures for water-20% glycerine. It was observed that the predicted values of water-20% glycerin system were in close agreement with the actual values.


Jialong Wang and Wei Wan (2009) investigated the effect of temperature, initial pH and glucose concentration on fermentative hydrogen production by mixed cultures in a batch test using central composite design. The modelling abilities of the response surface methodology model and neural network model, as well as the optimising abilities of response surface methodology and the genetic algorithm based on a neural network model were compared. The results showed that the root mean square error and the standard error of prediction for the neural network model were much smaller than those for the response surface methodology model, indicting that the neural network model had a much higher modelling ability than the response surface methodology model. The maximum hydrogen yield of 289.8 mL/g glucose identified by response surface methodology was a little lower than that of 360.5 mL/g glucose identified by the genetic algorithm based on a neural network model, indicating that the genetic algorithm based on neural network model had a much higher optimising ability than the response surface methodology. Thus, the genetic algorithm based on
neural network model was a better optimisation method than response surface methodology and could be recommended to be used during the optimisation of fermentative hydrogen production processes.

Thirumarimurugan M. et. al. (2011) conducted an experimental investigation to compare the heat transfer of a solvent and solution using Spiral Heat Exchanger. Steam was used as the hot fluid, whereas Water and Acetic acid-Water miscible solution served as cold fluid. A series of runs were made between steam and water, steam and Acetic acid solution. The volume fraction of Acetic acid was varied and the experiment was held. The flow rate of the cold fluid was maintained from 120 to 720 lph and the volume fraction of Acetic acid was varied from 10-50%. Experimental results such as exchanger effectiveness, overall heat transfer coefficients were calculated. The generalised regression model was used for Artificial neural network simulation using MATLAB and the data obtained was compared with experimental findings and found to be valid.

Moghadassi A.R. et. al. (2011) proposed a new method based on the artificial neural network (ANN) for the analysis of Shell and Tube Heat Exchangers. Special parameters for heat exchangers analysis were obtained by neural network and the required experimental data were collected from Kern’s book, TEMA and Perry’s handbook. The work used back propagation learning algorithm incorporating Levenberg- Marquardt training method. The accuracy and trend stability of the trained networks were verified according to their ability to predict unseen data. MSE error evaluation was used and the error limitation is 10-3-10-6. Parameters can be obtained without using charts, different tables and complicated equations. During this research, twenty two networks were utilised for all different properties. The results demonstrated the ANN’s capability to predict the analysis.

Wafa Batayneh et. al. (2013) optimised the heat sink dimensions by maximising the heat dissipation and minimising thermal resistance and pressure drop. A Neural network model was built for a parallel-plain fin heat sink. The model was developed using an experimental data from the literature. In addition, a quadratic model equation of the affecting parameters was constructed and analysed using Response Surface Methodology for determining the important factors affecting the performance of the heat sink, and the quadratic effect of every factor by using design of experiment,
analysis of variance and regression analysis. The results of the neural network model were compared with the experiment and it was shown that the error did not exceed 13.54%. The value was considered small and acceptable for such system.

Sivaraman E. (2014) has carried out extensive studies on ANN modelling and Model based controllers for a Shell and Tube heat exchanger to predict and control hot fluid outlet temperature with respect to variations in cold fluid inlet flow rate both in simulations and experimentations.

2.5.2 ANFIS Modelling

Jang J.S.R.(1993) presented the architecture and learning procedure underlying ANFIS (adaptive-network-based fuzzy inference system) which was a fuzzy inference system implemented in the framework of adaptive networks. By using a hybrid learning procedure, the proposed ANFIS could construct an input-output mapping based on both human knowledge (in the form of fuzzy if-then rules) and stipulated input-output data pairs. In the simulation, the ANFIS architecture was employed to model nonlinear functions, identify nonlinear components on-line in a control system, and predict a chaotic time series, all yielding remarkable results. Comparisons with artificial neural networks and earlier work on fuzzy modelling were listed and discussed. Other extensions of the proposed ANFIS and promising applications of automatic control and signal processing were also suggested.

Joo-Hwa Tay and Xiyue Zhang (1999) found that anaerobic biological wastewater treatment systems were difficult to model because of their complex performance and significant variation with different reactor configurations, influent characteristics, and operational conditions. Instead of conventional kinetic modelling, advanced neural fuzzy technology was employed to develop a conceptual adaptive model for anaerobic treatment systems. The conceptual neural fuzzy model contained the robustness of fuzzy systems, the learning ability of neural networks, and could adapt to various situations. The conceptual model was used to simulate the daily performance of two high-rate anaerobic wastewater treatment systems with satisfactory results obtained.

Arulselvi S.(2007) reported about a detailed design procedure and implementation of ANFIS modelling using MATLAB software for a nonlinear system.
Mullai et. al. (2011) investigated the performance of an anaerobic hybrid reactor (AHR) for treating penicillin-G waste water at the ambient temperatures of 30–35 °C for 245 days in three phases. The experimental data were analysed by adopting an adaptive network-based fuzzy inference system (ANFIS) model, which combined the merits of both fuzzy systems and neural network technology. The statistical quality of the ANFIS model was significant due to its high correlation coefficient $R^2$ between experimental and simulated COD values. The $R^2$ was found to be 0.9718, 0.9268 and 0.9796 for the I, II and III phases, respectively. Furthermore, one to one correlation among the simulated and observed values was also observed. The results showed the proposed ANFIS model was well performed in predicting the performance of AHR.

2.5.3 Fuzzy Clustering

Among the different fuzzy modelling techniques, the Takagi-Sugeno (T-S) model (Takagi and Sugeno 1985) has attracted the most attention. Fuzzy models can be seen as rule-based systems suitable for formalising the knowledge of experts, and at the same time they were flexible mathematical structures, which could represent complex non-linear mappings (Zeng and Singh 1994).

Special attention was focussed on the construction of fuzzy models from numerical data and the possibility of incorporating a prior knowledge about the system (Babuska and Verbruggen 1995).

Automatic generation of fuzzy if-then rules based on special modified fuzzy clustering algorithm was discussed by Klawonn and Annette Keller (1997). Fuzzy identification was an effective tool for the approximation of uncertain nonlinear systems on the basis of measured data was reported by Driankov et. al. 1998.

Knowledge acquisition, however is, a cumbersome task, and for partially unknown systems, human experts are not available. Therefore, data-driven construction of fuzzy membership function and rules from measured input/output data has received a lot of attention. Such modelling approaches typically seek to optimise some numerical objective function, while less attention is paid to the complexity of the resulting model in terms of the number of membership functions and rules. The construction of T-S fuzzy models based on different clustering techniques like Fuzzy
C-Means (FCM) and Geth and Geva (G-G) for chemical processes has been addressed by Babuska (1998).

Membership functions can be defined by the model developer (expert), using prior knowledge, or by experimentation, which was a typical approach in knowledge-based fuzzy control as reported by Abonyi et. al. 2001.

A method to supervise the process of fuzzy clustering for rule extraction in order to detect and remove less important clusters has been presented. The reduction was based on the orthogonal least squares approach to subset selection and adopted for fuzzy clustering (Setnes, 2000). The problem of identifying the parameters of the constituent local linear models of Takagi-Sugeno fuzzy model has been presented by Johansen and Babuska (2003).

The application of fuzzy clustering to the identification of T-S fuzzy models has been addressed and methods to extract T-S fuzzy models from fuzzy clusters obtained by G-K clustering were presented by Abonyi et. al.,(2001) and Abonyi J. and Birkhauster (2003).

A comparative study was made to prove that G-K fuzzy clustering technique was performing better for modelling and model based controllers for a Shell and Tube Heat Exchanger than FCM and G-G techniques have been addressed by Sivaraman (2014).

2.6 MOTIVATION FOR THE PRESENT WORK

On the strength of the exhaustive review of work done by the previous researchers, it is found that only countable work was done on Spiral plate Heat Exchanger (SHE).

- It is evident that most of the work had been done on developing correlations between the dimensionless parameters viz. Reynolds Number, Nusselt Number etc. From the literature, it is also observed that, the research focus was not much on optimising the overall heat transfer coefficient and pumping power in a Spiral plate Heat Exchanger with different operating fluid systems.
Moreover, the performance analysis of Spiral plate Heat Exchanger (SHE) using RSM optimisation and CFD modelling are not much reported in the literature. Hence an attempt is made in this work, to study the performance analysis based on the above said techniques.

Also, not much literature was reported about modelling to predict the unseen data. Author found that no literature have been reported so far about modelling of Spiral plate Heat Exchanger based on G-K fuzzy clustering technique.

Thus, the author is motivated to carry out the research on the areas which seem to have the potential, yet unattended. Hence, the performance analysis of SHE is planned by implementing RSM based experimentation and optimisation, CFD modelling and Intelligent modelling techniques.

2.7 PRESENT WORK

The present work aims to optimise the input process conditions namely, hot fluid flow rate, cold fluid flow rate and hot fluid inlet temperature in order to achieve the maximum possible overall heat transfer coefficient by consuming the minimum amount of pumping power. The experimental conditions are framed by the design of experiments technique incorporating response surface methodology. Experiments are conducted based on the Box- Behnken design for the fluid systems namely

1) Water - Water system
2) Water - Sea water (3%) system
3) Water - Sea water (12%) system
4) Water - Methanol system
5) Water - Butanol system
6) Water – Biodiesel system.

In all the fluid systems, water is chosen as the hot fluid for comparing the fluid systems uniformly. Also, the choice of water as the hot fluid results in the effective control over the heating process.