# Introduction

Here, at first, a short introduction about the Thermo-Fluid engineering has been given. Then soft computing techniques and their scope have been discussed in details. Why soft computing based techniques should use to handle the increasing complexities in the analysis of thermo-fluid problems have discussed in the next section. Then detailed discussions about the scope of work for the present thesis and corresponding literature review have been made. The gaps in the literatures and motivation behind the selection of the problems for the present thesis have been described after that. Then aims and objectives for the present work have been stated. Contributions made by the scholar have been stated after that. At last the layout of the thesis has been described.

## 1.1 Introduction to Thermo-Fluid Engineering

Energy is one of the key factors for the sustainable development of any human endeavour and also is the most essential element in the progress of science and technology. Engineering activities involve the extraction of energy (truly speaking the usable from of energy) from natural resources, its storage, exchange and transformation. The development of various disciplines of engineering is motivated by such activities. For example, one can name fluid dynamics and heat transfer. These two closely-related disciplines have been studied thoroughly and researched extensively mainly due to their importance in the field of energy.

Like many other engineering subjects, the understanding of both fluid dynamics and heat transfer was developed initially through experimental research. Gradually, scientists could translate their understanding in terms of physical theories and mathematical formulations. Then onwards, the research in these fields displayed an interwoven texture of both experimentation and theoretical prediction, as they supplement each other to a very great extent. Nevertheless, neither of these techniques is free from limitations. Experiments are time consuming and costly. Moreover, the physics revealed through experimentation is often limited due to inadequacy of the measurement techniques. The development and application of theoretical techniques faced a unique difficulty. It is a well-accepted fact that both fluid dynamics and heat transfer involve complex physics and are characterized by highly non-linear behaviour. Analytical solutions of the basic conservation equations often become formidable, if not impossible. The development of computational techniques and the growth of computational power over the years paved the path for the use of theoretical analysis for many practical problems. Much of the advancement in the field has been the result of first-principle analyses for the simpler phenomena, supplemented by experimental correlations for the more complex ones, for which the physics is either unknown or too formidable.

However, with the growth of technology the demand domain for theoretical analysis has been extended from straight forward equipment design and process analysis to optimization; online control; fault diagnosis; simulation of multi-scale, multi-physics complex systems; solutions of inverse problems etc. Hard computing techniques (Physics-based modelling and straight forward conventional techniques for their solutions) are often inadequate, time and cost intensive for such problems.

## 1.2 Soft Computing and its Scope

Past nearly three decades have seen enormous stride for the development of a special class of computation, radically different from the conventional computation of physics-based models (here after referred as hard computing), that can be loosely grouped together under the general term: soft computing. This development has been motivated by increasingly broader applications, which are difficult to handle by conventional approaches. Since, at the same time, relatively powerful computers have become commonly available, applications of these methods are quickly spreading to many areas of science and engineering outside the field of computer science, especially for complex systems, where the traditional methods have failed to be useful.

This is a highly multi-disciplinary activity. It involves concepts and methods from mathematics, computer science and engineering. Most interestingly, it borrows ideas from many natural phenomena as well as the behaviour and the functioning of living organisms. The strength of this work is to merge ideas, concepts and methods from these diverse areas and illustrate an optimization framework that is particularly tailored for practical engineering problems

The term 'soft computing' was introduced by Prof. Zadeh (1992). Soft computing can be described as the computer science part of bionics, where the understanding and transformation of principles from nature into engineering problems are investigated. Some of its principles are based on simplistic models of human intelligence and evolutionary experience, can be realized by very simple computational steps and often accompanied by a very large number of repeated or recursive computational cycles.

The functioning of human mind is tolerant of uncertainty, imprecision and partial truth. Hence, the name 'soft computing' is very befitting. It is obvious that under such preconditions, straight forward hard computing techniques based on the first principle will not succeed. Soft computing on the other hand, mimics many of the properties of living beings to achieve tractability, robustness and low solution cost. Soft computing is a collection of different biologically-inspired methodologies, such as evolutionary algorithms like Genetic Algorithm (GA), neural computing like Neural Networks (NN), Fuzzy Logic (FL); engineering-inspired methodology, namely Simulated Annealing (SA) (inspiration come from annealing in metallurgy); statistically-inspired methodology like data mining etc. These methodologies and their different combined forms like GA-NN, NN-FL, GA-FL, GA-FL-NN exhibit superior capability in tolerating the impression and uncertainty of the problem and provide an option to solve problems that are computationally complex or mathematically intractable. It is interesting to note that each member of this family is based on very different natural phenomena and is able to perform some specific type of tasks. For example, GA is a powerful tool for search and optimization, which works based on Darwin's principle of natural selection (that is, survival of the fittest). NN is an important tool for learning and adaptation. NN adopts the way human beings process information through the natural neural system. FL is a potential tool for dealing with impression and uncertainty. Each of these members has its inherent strength and limitations. In coupled techniques (like GA-NN, NN-FL, GA-FL, GA-FL-NN), two or three constituent tools are combined to get the advantages from both of them and to remove their inherent limitations. Thus, the main advantage provided by soft computing stems from the fact that the functions of the constituent members are complementary and synergistic in nature, as there are no competitions among themselves. Therefore, different techniques can readily be combined to increase the capability of problem solving.

Soft computing does not require any extensive mathematical formulation of the problem. Algorithms developed based on soft computing are adaptive in nature and can accommodate the changes of a dynamic environment. In recent years, the uses of soft computing-based methodologies have received much attention as an alternative approach to cope with real-world problems. They have been used in a wide variety of applications in both the natural and engineering sciences, among which are decision making, pattern recognition, system control, information processing, natural languages, optimization, speech recognition, vision and robotics etc. Each member of the soft computing family has received in-depth development in the recent past. Moreover, different combinations of these techniques are also being tried continuously.

## 1.3 Why Soft Computing in Thermo-Fluid Engineering

With the increasing demand for better utilization of energy, compactness of system, environment friendly operation, accurate control, safety and reliability, engineering systems are becoming more complex. Thermo-fluid systems are no exceptions. As a consequence, engineers are required to use multifaceted tools comprising of physics-based theoretical analysis, correlations derived from experiments, heuristics as well as techniques from the domain of soft computing to achieve the effective yet competitive solutions. Engineers have recognized that the techniques based on soft computing have much to offer, when the ultimate goal is to detect and make use of patterns rather than to uncover new physics. Accordingly, an upsurge in the application of these techniques to thermo-fluid problems has been noticed in the recent past.

To clarify the above points further, one may take the example of a typical thermal system like heat exchanger. Heat exchangers are of diverse configurations and constructions. Fin-tube heat exchangers (as shown in Figure 1.1) are very common in HVAC (Heating, Ventilating, and Air Conditioning) applications and can be considered for the present purpose. In a fin-tube heat exchanger, air passes through the finned passages while the refrigerant flows through the tubes in a cross-flow arrangement. A common engineering problem could be the prediction of the exit temperature of the fluid streams for known inlet parameters and heat exchanger geometry. Such a prediction becomes a formidable task, if it is attempted from the first principle (say, different conservation equations). The factors, which complicate the situation are maldistribution of refrigerant from the header, entrance length and bend effect on flow and heat transfer, variation of air temperature along the fin length, vortices in the neighbourhood of tube-fin junctions, effect of natural convection, if any, phase change of the tube side fluid, axial conduction through the metallic matrix and axial dispersion through the fluid etc. It may be noted that the list is far from the exhaustive. In most of the cases, the conventional analysis ignores these complicacies. In fact, even though separate analysis can be done for one or a couple of factors together, it becomes impossible or cost-prohibitive to incorporate all the factors together. Then, one may think of the complicacies, which occur in such heat exchangers during dynamic operation. These include fouling, frost growth, movement of the two-phase boundary in the tube side, movement of the dry and wet region boundary on the fin side. In many cases, deterministic modelling is not possible for these phenomena. One may imagine well the shortcomings of a deterministic model, if the equipment is to be controlled based on real-time performance prediction.

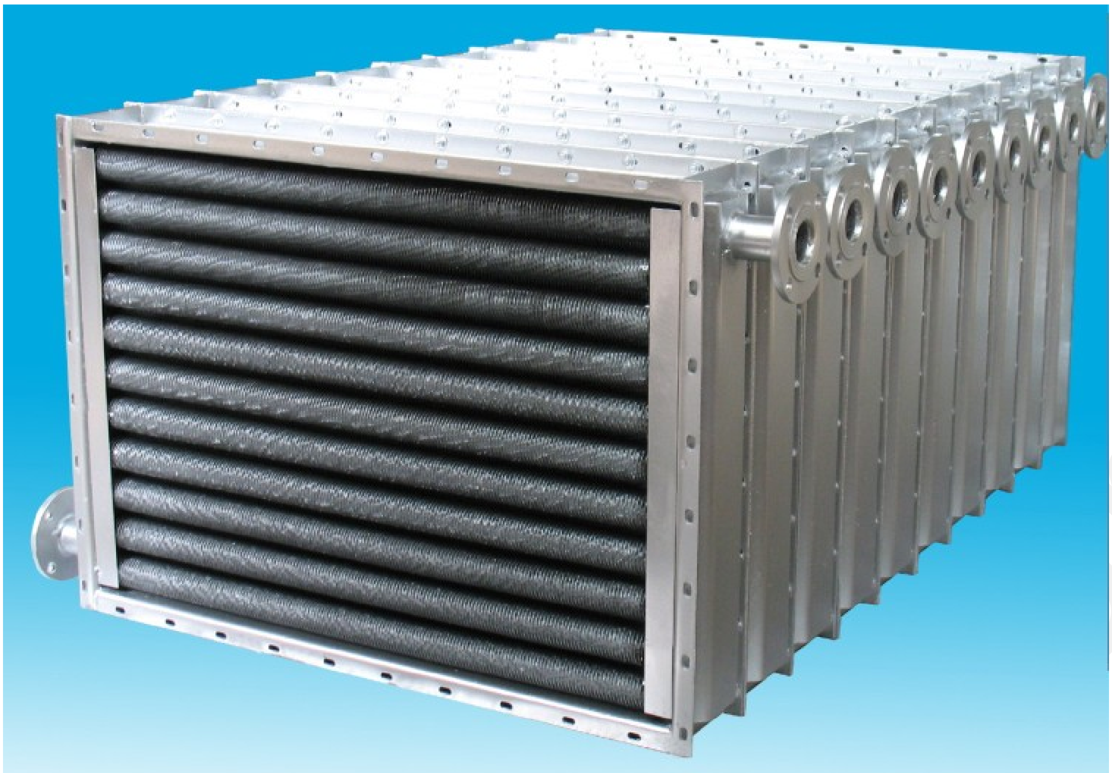

Figure 1: 3D view of a fin-tube heat exchanger.

It may be noted that traditionally, empirical relations are used to circumvent some of the difficulties narrated above. But, conventional practices of deriving empirical relationship are not free from human bias. They are often very static input-output relationships, which fail to take care of the inherent dynamics, non-linearity and fuzziness. These limitations become prominent in problems of control, fault diagnosis and prognosis. Different techniques of soft computing can be used judicially to obtain the engineering solution of many such problems. It is, therefore, not surprising to see that that a number of endeavours have been made in the recent past to apply soft computing techniques in diverse problems of the thermal engineering. It is also interesting to note that several researchers, renowned for their contributions in hard computing, are favouring soft computing techniques for some typical problems in thermal engineering. A quick glimpse of this activity can be appreciated from the brief survey given in the next paragraph.

Sen and Yang (2000) extensively described the soft computing-based methodologies: NN and GA, and their scope in the field of thermal engineering. For the control of thermo-fluid equipment, the use of fuzzy logic (Santos and Dexter, 2002; Petermeier et al., 2003; Ghosh et al., 2005; Ruiz-Mercado et al., 2006; Maidi et al., 2008; Annand and Jeyakumer, 2009; Stephen et al., 2010), neural network (Diaz et al., 2001a, 2001b, 2004; Varshney and Panigrahi, 2005; Davis et al., 2008; Moon et al., 2009) and combined neural network and simulated annealing (Sarkar and Modak, 2003) had demonstrated considerable advantage. The detail scopes of soft computing techniques in the field of thermal control had been discussed by Sen and Goodwine (2002) and Sen (2003). In diverse thermal systems, heat exchangers are very common. NN had frequently been used for the prediction, simulation and modelling of heat exchangers (Pacheco-Vege et al., 2001a; Pacheco-Vege et al., 2001b; Riverol and Napolitano, 2002; Islamoglu, 2003; Islamoglu et al., 2005; Lecoeuche et al., 2005; Kumar et al., 2006; Xie et al., 2007; Fadare and Fatona, 2008; Duran et al., 2009; Peng and Ling, 2009). For the optimal design of heat exchangers (Ozkol and Komurgoz, 2005; Hilbert et al., 2006; Selbas et al., 2006; Ozcelik, 2007; Kumar et al., 2008; Cavazzuti and Corticelli, 2008; Xie et al., 2008; Wu et al., 2008; Ponce-Ortega et al., 2009; Copiello and Fabbri, 2009; Mohagheghi and Shayegan, 2009) and synthesis of heat exchanger networks (Dipama et al., 2008; Luo et al., 2009; Ravagnani et al., 2005; Ponce-Ortega et al., 2008), GA had been used by several researchers. SA-based approach had been used by some researchers (Wei-zhong et al., 2008; Wei-zhong and Gang, 2009) for the optimal synthesis of heat-integrated distillation. A combination of GA and SA was used by Ma et al. (2007, 2008) to synthesize the multi-stream heat exchangers network. Compact heat exchangers had been simulated by Pacheco-Vega (2002) using soft computing-based technologies.

A detail review of the utilization of GA in heat and mass transfer problems had been made by Gosselin et al. (2009). They showed that although the GA had been developed in 1970s, the utilization of GAs in the field of heat transfer is more recent. In particular, the last couple of years had seen a sharp increase of interest in GAs for the heat transfer-related optimization problems. Several simulations need to be performed in a GA operating procedure but, the computational times required for most of the numerically simulation problems, in which heat transfer community is interested, are very long. Therefore, the overall computational time required for the complete GA run could be prohibitive, if the design simulation involves CFD analysis. This is probably the reason behind the fact that utilization of GA in heat transfer problem is more recent.

In some other recent review papers, Yang (2007, 2008) showed that several soft computing and artificial intelligence-based methodologies were able to provide very promising results to deal with the type of complexity mentioned above. He concluded that though the tools developed based on soft computing technique are ideal to handle the increased complexity in thermo-fluid engineering, their applications to thermal problems are still rather tentative. In those reviews, he described the soft computing-based methodology as a new paradigm for analysing thermal problems. His review will encourage many more thermal engineers and practitioners to seriously consider soft computing techniques for treating future critical thermal problems, which are difficult to treat by traditional means.

## 1.4 Scope of the Present Study and Literature Review

In the previous section, it has been emphasized that the traditional methods (analytical, computational and experimental) alone may fail to provide any successful practical solutions for many of the complex real-life thermo-fluid problems. In some cases, they cannot be solved solely by the traditional methods. Incorporation of suitable soft computing-based methodologies can improve the solution or can reduce the cost and effort of obtaining it. Consequently, the emphasis has been given in the present work on the synergetic combination of the conventional techniques of investigation with soft computing-based methodologies.

It goes without saying that a large number of thermal-fluid engineering problems can be benefitted by the application of soft computing based techniques. However, within the limited scope of the present dissertation, four problems have been carefully selected to establish the flexibility and versatility of this approach. In all the problems, either CFD analysis or experimentation has been amalgamated with one or more soft computing tools to arrive at a better solution. The general introduction and brief literature review for each of these four problems are given below separately.

### 1.4.1 Duct shape optimization through hybrid computing

**Shape optimization:** Optimization has become an inseparable step of the design process in many of the engineering systems. From the engineering point of view, the main motive for the optimum design has been a reduction in initial cost, operating cost or both under a set of constraints, which are dictated by the diverse parameters like process requirements, available infrastructure, safety, environmental concern etc. Based on the above goal, a set of design variables is optimized. For a thermo-fluid system, such relevant output variables could be shear stress in biomems, efficiency of a pump, rate of heat transfer in a cooling system, drag of a car body or pressure drop in a pipe network. Such optimization exercise not only aims to find out the suitable process parameters but also often seeks the optimum shape of the physical system.

Shape optimization is a classical problem. From time immemorial, it was known that a curve of a given length encompasses the largest area if it becomes a circle. One can also refer to the Brachistochrone problem, which was posed to the then scientific community by Johann Bernoulli in 1696 (Padra, 2006). In this problem, one needs to find out the shape of the curved path between two points in a vertical plane such that a point mass takes the minimum time to slide along it. Even a genius like Sir Isac Newton was attracted to the mathematical rigor of the problem and the result was the beginning of calculus of variation! (Padra, 2006; Desaix et al., 2005). Over the years, various shape optimization problems have been taken up by the scientific and engineering community. As the present work is concerned with the optimum design of a fluid flow system, a brief overview of some of the shape optimization exercises in thermo-fluids engineering is given below.

The process of optimization for thermo-fluidic systems most often contains two steps. The objective function is computed from the hydrodynamic and heat transfer simulations through various analytical or numerical methods. An optimization algorithm is used next to determine the design variables, which optimizes the objective function. Again, diverse techniques of optimization ranging from classical gradient-based methods and search algorithms to evolutionary programs are in use. Fabbri employed a Genetic Algorithm (GA) for the optimization of both corrugated wall channel (Fabbri, 2000) as well as internally finned tubes (Fabbri, 1998; Fabbri, 2004). Arrangement and determination of optimal shapes of staggered pin fins in the channel of a plate heat-exchanger was attempted by Lee et al. (2001). A numerical and experimental geometric optimization for general staggered configurations had been studied by Matos et al., 2004, to maximize the total heat transfer rate among a bundle of finned or non-finned tubes in a given volume. By using various multi-objective optimization methods, optimal results for a micro-heat-exchanger had been obtained by Okabe et al., 2003.

A large volume of work had been carried out on shape optimization of fluid flow systems relevant to aerodynamics applications (Mohammadi and Pironneau, 2001; Dulikravich, 1992). Falco (1997) carried out optimization of aerofoil shapes using evolutionary algorithms. Multi-objective design optimization in aerodynamics and electromagnetics was conducted by Mäkinen et al. (1998). Several non-linear optimization problems related to general fluid flow had been solved using gradient-based optimization tools by various investigators (Baysal and Eleshaky, 1992; Reuther et al., 1999a, 1999b; Bängtsson et al., 2003; Mohammadi et al., 2003). A shape optimization of cut-off in a multi-blade fan/scroll system was done by Han and Maeng (2003) using two dimensional CFD. A flow solver and a mathematical optimization tool (implementation of a trust region-based derivative-free method) were combined and used as an integrated procedure by Lehnhauser and Schafer (2005) for the shape optimization of a fluid flow domain.

Diffusers or nozzles are integral parts of many flow systems. A diffuser is used to connect a lower diameter pipe with a larger diameter one. The main purpose of using diffuser is to either recover static pressure or minimize total pressure loss in a pipe/duct. An improperly designed diffuser may lead to flow separation and excessive consumption of pumping power. It may also produce a flow mal-distribution in the downstream, which is not acceptable in many applications. Moreover, a constraint of restricted length is often imposed on the design. As a result, designing the optimum shape of a diffuser had been the subject of investigation for many researchers during the last decade. Optimum design of a straight-walled diffuser was obtained by Kline et al. (1959). Four common optimization problems were analyzed and optimal solutions were located in relation to the overall flow regimes in terms of geometrical parameters for the straight-walled unit. The performance of a straight two-dimensional diffuser had been studied and analyzed by Reneau et al. (1967). The effect of wall shape on flow regimes and performance had been studied in a straight two-dimensional diffuser by Carlson et al. (1967). The profile of a plane diffuser with given upstream width and length had been optimized to obtain the maximum static pressure rise by Cabuk and Modi (1992). The steady-state Navier-Stokes equation was used to model the flow through the diffuser considering two-dimensional, incompressible and laminar flow. A set of adjoint equations had been solved to get the direction and relative magnitude of change in the diffuser profile that lead to a higher pressure rise. Repeated modification of the diffuser geometry with each solution to the direct and adjoint set of partial differential equations leads to a diffuser with the maximum static pressure rise. Geometries for three-dimensional viscous flow had been optimized by Svenningsen et al. (1996), applying quasi-analytical sensitivity analysis. The optimization tool had been applied on a two-dimensional laminar diffuser in order to maximize the pressure recovery by contouring the divergent wall section and the performance of the diffuser was found to improve by about 5% compared to that of straight-walled geometry. A response surface technique had been used to optimize the shape of a two-dimensional diffuser subjected to incompressible turbulent flow by Madsen et al. (2000). The shape of diffuser wall was described using polynomial and B-splines with two and five design variables, respectively. They also applied monotonicity condition, which drastically reduced the design space. Growth-Strain Method was used for shape optimization in a flow system by Maeng and Han (2004). They optimized the shape by assuming a distributed parameter like dissipation energy to be uniform in a flow system. A diffuser had been optimized using the Support Vector Mechanics (SVM) by Fan et al. (2005). The SVM was used to construct a response surface. In that study, the optimization was performed on an easily computable surrogate space. Shape optimization was carried out by Goel et al. (2007) to improve hydrodynamic performance of diffuser vanes of a pump stage. Bezier curves and circular arcs had been used to define the shape of the vanes. To identify the regions of the vane that have a strong influence on its performance, surrogate model-based tools were used. In the absence of manufacturing and stress constraints, optimization of the vane shape led to a nearly 8% reduction in the total pressure losses compared to the baseline design by reducing the base separation.

The shape optimization of systems involving fluid flow has been considered for the present thesis. However, one needs to be cautious in selecting the optimization technique for the present nature of the problem.

**Hybrid computing:** Hybrid computation can be assumed as the application of the philosophy of hybrid systems in the field of computation. Hybrid computing has received considerable attention recently as an approach to achieve significant performance gains in many problem domains. Probably, one of the main problems encountered by the true application of computer algebra to applied domains is based on the fact that mathematical tools for modelling are far away from the kind of objects, which are tried to incorporate in CAS (Computed Algebra Systems). There are lot of evidences of inadequacy between the tools plugged in the CAS and the expectations of technological fields. Of course, one can work on the interfaces between numerical analysis and CAS, but the softwares like MATLAB offer more than what is necessary to a wide range of engineers. So, the requirements of tools for modelling in applied fields are more than the mathematics, which are put in the CAS. After all, the mathematics is also driven by the applications. Hybrid computation works based on several ideas coming from computer science and gathered in the field known as hybrid systems. It is at the intersection of applied and traditional mathematics.

Most of the models used in physics and applied mathematics are basically approximate ones. The modelling process itself is an art, whose central skill is the approximation. How these central facts are taken into account? It is this point that is incorporated into hybrid computation. It is at the intersection of numerical analysis and computer algebra. A fundamental point in numerical analysis lies with the basic methodology in handling of evaluation functionals. However, computer algebra is able to offer the real handling of certain classes of functionals. So, the idea lies with the use of reasonable basic functionals instead of the evaluation.

The basic concept of hybrid computing had been explained by Dora et al. (2001). A technique was developed to simulate cylindrical grinding process using hybrid computing by Rowe et al. (1973). Another technique was suggested for processing of coronary haemodynamic data with a small hybrid computing system by Lavelle et al. (1973). A hybrid intelligent computing had been used in mineral resources evaluation by Tutmez (2009). A soft computing methodology, i.e. Artificial Neural Network (ANN)-based fuzzy modelling, had been presented for grade estimation and its stages had been demonstrated. A neuro-fuzzy method was used for preliminary clustering and finally, it could estimate the ore grades based on radial basis function neural network and interpolation. Chamberlain et al. (2008) presented their vision of the application development languages and tools that they believed would greatly benefit the process of designing, implementing and deploying applications on hybrid systems. A hybrid approach was developed for constrained evolutionary computing in case of product synthesis by Liang and Huang (2008). Swanson et al. (1971) had described a hybrid computing system for online human respiratory studies. A hybrid algorithm had been developed for computing permanents of sparse matrices by Liang et al. (2006).

The performance of a hybrid methodology combining neural network, fuzzy logic and genetic algorithm was tested for forecasting of irrigation water demand by Pulido-Calvo and Gutiérrez-Estrada (2009). A new stochastic method named Hybrid Generalized Extremal Optimization (HGEO) had been proposed by Xie et al. (2009) to compute the optimal power consumption for semi-track air-cushion vehicle. Another hybrid algorithm had been developed for discrete event simulation-based supply chain optimisation by Yoo et al. (2010). A quadratic approximation-based hybrid genetic algorithm had been used for function optimisation by Deep and Das (2008). A hybrid genetic algorithm for multi-objective optimisation problems with activity analysis-based local search had been developed by Whittaker et al. (2009). Two new computing models, namely a fuzzy expert system and a hybrid neural network-fuzzy expert system, had been presented by Dash et al. (1995) for time series forecasting of electric load. An effective hybrid quantum-inspired evolutionary algorithm for parameter estimation of chaotic systems had been developed by Wang and Li (2010).

The shape of a vane leading-edge fillet had been optimized by Lethander et al. (2004) to reduce the secondary flow in order to get minimum turbine vane passage adiabatic wall temperatures in a gas turbine. Gambit had been used to grid the complex geometry of fillet, and Fluent had been used as the CFD computation tool. The software iSIGHT (that provides a number of different optimisation algorithms) had been used as optimization tool.

Marco et al. (1999) had studied on multi-objective shape optimization in aerodynamics. They had basically applied GA to multi-objective optimization of aerofoil profiles. The objective functions, which are basically the aerodynamics coefficients had been deduced from the numerical simulation of the compressible flow around aerofoil geometry.

### 1.4.2 Stacking pattern optimization of multi-stream plate-fin heat exchanger

Heat exchangers are unique thermal equipment, which facilitate the exchange of thermal energy among various fluid streams. As heat exchangers cover an exceedingly wide range of applications, numerous designs have been evolved over the years. Those designs not only vary in configuration and size but also have different working principles. Historically, two-stream exchangers were conceived first and till today, the majority of exchangers belong to this category. Nevertheless, to cope with the continuous demand for high compactness, low capital and running costs, the engineers thought of encasing more than two streams in a single envelope. Such a device is termed as a multi-stream heat exchanger, where the streams (or at least one of the streams) will have more than one thermal communication. Various designs of multi-stream heat exchangers are in use. The simplest configuration could be a concentric tube three-stream heat exchanger, in which only the intermediate fluid stream will have more than one thermal communication. Besides this, shell and coiled tube type, plate and frame type and plate-fin type are the main varieties available. In many of these varieties, there is a limitation as far as the number of streams is concerned. For example, shell and helical exchangers are able to handle one cold and two or more hot streams or vice-versa.

In this respect, plate-fin heat exchangers enjoy a great flexibility, as there is no restriction on the number of hot and cold streams. A plate-fin heat exchanger with as many as ten or twelve fluid streams is not uncommon in industry. Plate-fin heat exchangers offer a number of advantages. For example, with a small volume and weight, it offers a high thermal performance. The pressure drop through such units is moderate, while the approach temperature could be very close. The possibility of parallel or cross arrangement of fluid streams and their intermediate entry and exit offer additional flexibility in the design of these exchangers. The main concerns behind the use of plate-fin heat exchangers for multi-fluid applications are the limited ranges of temperature and pressure, at which they can operate and the restrictions regarding their applicability to relatively clean fluids. Nevertheless, these heat exchangers are widely used in cryogenics and other process plants.

Over the decades, the analysis and design of two-stream heat exchangers got standardized. Both theoretical models as well as computational algorithms are available even for handling the cases of variable properties of the fluids, non-uniform heat transfer coefficient, phase change, axial conduction, axial dispersion etc. Unfortunately, the design procedure of multi-stream heat exchangers is still under development due to its inherent more complexity compared to the design of two-stream exchangers.

Features like bypass heat transfer (Haseler, 1983) or crossover in temperature (Fan, 1966), which are common in multi-stream heat exchangers, have no equivalence in two-stream units. The unique parameters like effectiveness, Number of Transfer Units (NTU) or Log Mean Temperature Difference (LMTD) have simplified the analysis and design of two-stream heat exchangers. The designers are yet to find out equivalence of such parameters in case of multi-fluid heat exchangers. A brief appraisal of various design methodologies suggested for the plate-fin heat exchangers is given here. In the simplest form, a multi-stream heat exchanger consists of three different streams. Sorlie (1962) developed a design theory for three-fluid heat exchangers of the concentric-tube and plate-fin types, in which the intermediate and cold streams were thermally insulated. Aulds and Barron (1967) extended the work of Sorlie (1962) by analyzing the case, in which all three streams were in thermal communication, as it is relevant for many three-fluid heat exchangers used in cryogenic systems. Pioneering work on multi-channel, parallel flow heat exchangers was carried out by Kao (1961) and Wolf (1964). It had been shown by them that in the absence of the effect of axial conduction through the separating wall, the basic equations describing the process of heat transfer in a multi-channel heat exchanger are a set of linear differential equations involving the temperatures of the fluids and the separating walls. A similar approach had been adopted by Zaleski (1984) to analyse multi-channel heat exchangers with unconnected channels, particularly lamella-type, plate-type, and helix-type units. Chato et al. (1971) suggested a method of dividing the heat exchanger into a large number of smaller sections over which physical properties remain approximately constant. Haseler (1983) proposed a novel solution methodology termed as constant wall temperature assumption. Based on this, the temperatures of all the separating walls were assumed to be equal at any cross-section normal to the flow direction. Prasad and Gurukul (1987, 1992), in their formulation of the differential method for design of plate-fin heat exchangers, applied the same simplified idealization. Prasad (1991, 1996a, 1997) employed the modified shooting method to solve the governing equations. Luo et al. (2001) developed an analytical model of a multi-stream exchanger with constant physical properties. In a separate paper, Luo et al. (2002) proposed a more generalized analytical solution for predicting the thermal performance of multi-stream heat exchangers and their networks.

Pinch Technology is a method usually adopted for the analysis of heat exchanger networks. Polley and Picon-Nunez (2001), Picon-Nunez and Polley (2000) and Picon-Nunez et al. (2002) extended this technique for multi-stream plate-fin heat exchangers using the temperature vs. enthalpy diagrams or composite curves. Wang and Sunden (2001) presented a new methodology for the design of multi-stream plate-fin heat exchangers through optimization of heat exchanger networks. Ghosh et al. (2006) suggested an alternate algorithm for the analysis of multi-stream plate-fin heat exchangers. Two key concepts had been used by them. The multi-stream heat exchanger had been conceived as a combination of a number of overlapping two-stream heat exchangers. This needs apportioning the heat exchanger area between different streams, which had been achieved by area splitting method. Next, the heat exchanger had been progressively subdivided in the axial direction by successive partitioning method to improve the accuracy of prediction.

As the thermal engineers always face the challenge of improving the performance of heat exchangers under constraints of varied nature, various efforts had been made to optimize the design of plate-fin heat exchangers. One of the earliest efforts of optimizing the stream arrangements of a multi-stream plate-fin heat exchangers is due to Fan (1966). He recommended a methodology for finding out the optimum arrangement of streams through the fragmentation of individual streams. In this context, clearly specified recommendation has been prescribed by Suessman and Mansour (1979). They proposed a technique for arranging the fluid streams, such that the resulting stacking pattern becomes close to the optimum, if not the optimum. According to them, for an optimum stacking pattern, the value of the cumulative heat load should change its sign, as one moves from one stream to the next. It may be noted that Prasad (1996b) had also used the technique of Suessman and Mansour (1979) for studying the layer stacking pattern in multi-stream heat exchangers. However, Prasad (1996b) used the concept of "half fin idealization", while analyzing multi-stream exchangers and studying the layer stacking pattern effect. The idealization used in the paper was quite weak. Later on, Prasad (1996a, 1997) had been successful in formulating the fin equations of multi-stream heat exchangers in a generalized way and solving them iteratively.

On the other hand, Yuan et al. (1997) suggested a different technique for designing a multi-stream heat exchanger involving two steps. In the first step (predict), the initial design of the exchanger was made through a local balance principle. In the second step (correct), the passage arrangement was readjusted using the results of differential computation of the temperature distribution. Three case studies were presented to establish the feasibility of the proposed method.

Parallel efforts are also made to optimize the design of multi-stream exchangers through different programming techniques and soft computing methodologies. A multivariate optimization of plate-fin heat exchangers had been carried out by Sunder and Fox (1993). They employed non-linear programming (NLP) to design a brazed aluminium plate-fin type compact heat exchanger. A multivariate objective function was minimized subject to several constraints. An approach was developed by Peng and Ling (2008) for the optimization of plate-fin heat exchangers (PFHE) using a Neural Network (NN) coupled with a Genetic Algorithm (GA). The major objectives of their PFHE design were the minimum total weight and total annual cost for a given set of constrained conditions. Total length and width of PFHE core, number of hot side layers, fin height and pitch on each side of PFHE were considered as the variables to be optimized by means of a GA combined with the Back-Propagation Neural Network (BPNN). A GA-based optimization technique had been developed for cross-flow plate-fin heat exchangers by Mishra et al. (2004). The aim of optimization was to minimize the total annual cost for a specified heat duty under given space and flow restrictions. In another paper, Mishra and Das (2009) optimized the thermo-economic cost for a cross-flow offset strip-fin heat exchanger with the specified heat loads under given space restrictions.

Picón-Núñez and López Robles (2005) suggested a unique technique for flow passage arrangement of multi-stream heat exchanger. The main feature of their approach was uniform heat load per passage. This had been achieved by selecting suitable secondary surface and fin geometry. They considered equal number of hot and cold passages and the number of passages allocated to a given stream was directly proportional to its heat capacity flow rate. They had also proposed a simple model for the steady flow of the multi-stream heat exchanger.

In the past decade, efforts had also been made to synthesize multi-stream heat exchangers as a heat exchanger network (HEN) problem. In many cases, such networks had been optimized. It was identified (Luo et al., 2004a) that such synthesis problems with a large number of streams might have more than one optimum solutions. The difficulty of solving such problems compelled the researcher to adopt different evolutionary techniques like a combination of genetic algorithm and simulated annealing (Luo et al., 2004a; Ma et al., 2008), improved genetic algorithm (Luo et al., 2004b) etc. Improvement in GA was required to handle the problem of mixed-integer nonlinear programming (Wei et al., 2006) and to avoid the premature convergence. Luo et al. (2009) proposed a hybrid scheme by combining GA with simulated annealing algorithm, local optimizing strategy, structure control strategy and other strategies to improve the structural search ability of the algorithm substantially. Fieg et al. (2009) used a two stepped procedure for the synthesis of a large scale heat exchanger network. In the first step, a hybrid GA was used for the entire network. In the second step, the optimization of sub-networks was achieved through a monogenetic algorithm.

### 1.4.3 Inverse estimation of boundary in heat conduction

Mathematically, inverse problems belong to the class of ill-posed problems, that means, their solutions do not satisfy the general requirement of existence, uniqueness, and stability under small changes to the input data. During last two decades, the inverse heat conduction problems had attracted much attention of the researchers due to their numerous importances in science and engineering. Beck (1970) used a finite-difference approximation in conjunction with a least squared fit and a method of nonlinear estimation to solve the inverse conduction problem. A numerical procedure for determining the heat flux to a thermally thick wall with variable thermal properties had been developed by Howard (1968) utilizing a single embedded thermocouple. To solve the ill-posed inverse heat conduction problem, analysis had been carried out by Weber (1981). A method for computing the thermal diffusivity of a solid, based on a computer-assisted evaluation of the solution of the transient inverse heat conduction problem had been developed by Lordanov and Steward (1984). A new solution procedure was proposed by them for the one-dimensional case, which replaced the heat conduction equation with an approximate hyperbolic equation. Three-dimensional formulation had been presented to solve inverse heat conduction as a general optimization problem by applying an adjoint equation approach coupled to conjugate gradient algorithm by Jarny et al. (1991). A solution technique for random and nonlinear inverse heat conduction problem had been developed by Riganti (1991). To estimate the initial and boundary conditions in a two-dimensional hollow cylinder simultaneously, a linear inverse model had been constructed by Hsu et al. (1998). Two-dimensional inverse heat source problem had been solved through the linear least squared error method by Yang (1998). A new method had been adopted by Fang et al. (1997) to solve the inverse conduction problem in steady heat flux measurement. Here, basically a procedure was proposed for determining steady heat fluxes on boundaries based on the linear superposition theorem, which pose an inverse conduction problem. An attempt had been made to solve the inverse heat transfer problem using the Karhunen_Loéve Galerkin method by Park et al. (1999). To estimate the temperature-dependent thermal conductivity, an inverse heat conduction problem had been solved by Yang (1999). Fourier analysis of conjugate gradient method had been applied to inverse heat conduction problems by Prud'homme and Nguyen (1999).

An inverse model had been used to estimate the wall heat flux in film condensation on a vertical surface by Hsu et al. (2000). The inverse steady state convection problem in a porous medium had been solved by adjoint equations and conjugate gradient by Prud'homme and Nguyen (2001). An inverse radiation problem had been tackled by Park and Yoon (2001) using the Karhunen-Loéve Galerkin procedure. The low-dimensional model obtained by the Karhunen-Loéve Galerkin procedure had been employed to solve the inverse radiation problem of estimating the related parameters from the temperature measurement in three-dimensional participating media, where radiation and conduction occur simultaneously. Numerical solutions had been obtained for the case of a rectangular enclosure subjected to an unknown heat flux on one side, and to known conditions on the remaining sides. The inverse analysis was based on film condensation thickness readings taken at several different points on the plate. An attempt had been made to estimate the surface temperature through two-dimensional inverse heat conduction problems by Chen et al. (2001). A hybrid numerical algorithm of the Laplace transform technique and finite-difference method with sequential-in-time concept and the least-squared scheme had been proposed to predict the unknown surface temperature of two-sided boundary conditions for two dimensional inverse heat conduction problems by Chen et al. (2002). An attempt had been made to identify the thermal conductivity through application of inverse solution using the finite element method by Telejko and Malinowski (2004). For estimating the boundary condition in electronic device, an inverse non-Fourier heat conduction problem had been solved by Hsu and Chu (2004). Thermal conductivity had been investigated for upsetting with a procedure of combining inverse model and proposed regularization of Tikhonov method by Lin and Lin (2005). A study had been intended to provide an inverse method for estimating the unknown boundary condition in a 3D non-Fourier hyperbolic heat conduction problem by Hsu (2006). An attempt had been made to inversely estimate the thermal behaviour and viscosity of fluid between two horizontal concentric cylinders with rotating inner cylinder by Hsu (2008). Wall condition on a rotating cylinder had been estimated using practical application of inverse heat conduction by Volle et al. (2009). A method for determining fireside heat flux, heat transfer coefficient on the inner surface and temperature of water-steam mixture in water-wall tubes had been developed by Duda and Taler (2009), where the unknown parameters are estimated based on temperature measurement at a few internal locations from the solution of the inverse heat conduction problem. An inverse method had also been developed by Taler et al. (2009) to identify local heat flux to membrane water-walls in steam boilers.

A non-classical method based on neural network had been used by Raudenský et al. (1995) to solve an inverse heat conduction problem for boundary conditions and time constant of a temperature sensor on the basis of the knowledge of temperature reading from that sensor. To analyze inverse heat conduction problems (IHCPs), a technique was proposed by Hara et al. (1999) using neural networks, which could identify unknown boundary conditions for multidimensional steady or transient problems. Two different artificial neural networks, namely multilayer perceptron (MP) and radial basis function (RBF) were used by Shiguemori et al. (2002) for estimating time-dependent boundary conditions in a slab. The temperature-time series obtained from a probe placed next to the boundary of interest was used as inputs to the NN. A methodology had been proposed by Shiguemori et al. (2004) to solve one-dimensional parabolic inverse problems using three neural network (NN) models to determine the initial temperature profile on a slab with adiabatic boundary condition, for a given transient temperature distribution during a time. Both forward and inverse heat conduction problems had been solved using neural network by Deng and Hwang (2006) to identify the unknown boundary conditions. They used a continuous-time analogue Hopfield neural network to compute the temperature distributions in forward heat conduction problems and a back-propagation neural network (BPNN) to solve inverse heat conduction problem. For analyzing inverse heat conduction problems, an efficient technique had been developed using a Kalman Filter-enhanced Bayesian Back-Propagation Neural Network (KF-B2PNN) by Deng and Hwang (2007). The training data required for the KF-B2PNN were prepared using the continuous-time analogue Hopfield Neural Network. An inverse problem was solved by Lecoeuche et al. (2006) using a recurrent neural network to estimate the heat flux applied on one side of a structure from the knowledge of the temperature measured at other side of the structure (standard one-dimensional conducting bar). An inverse heat conduction problem with internal heat source in cylindrical coordinates had been solved by Cortes et al. (2007) using a feed-forward with back-propagation algorithm. Moreover, Hwang and Deng

(2008) proposed a technique for the solution of inverse heat conduction problems in a gun barrel using a three-layered BPNN to estimate the heat flux of inner surface of the barrel.

### 1.4.4 Diagnosis of counter-current two-phase flow

Gas-liquid two-phase flow through a conduit could be manyfold more complex compared to the hydrodynamics pertaining to the flow of only one of this fluid pair through the same conduit. This is because, during two-phase flow, the two phases can distribute themselves in a large number of spatio-temporal arrangements known as flow patterns or flow regimes. Any transport phenomena during two-phase flow, namely momentum, heat or mass transfer is strongly influenced by the existing flow regime. The occurrence of a flow regime, on the other hand, is dependent on a large number of parameters like the velocity and properties of the individual phases, shape and size of the conduit cross-section, direction of flow with respect to gravity (up, down or inclined) and with respect to the motion of the companion phases (co-current or counter-current), effect of body force, effect of heat and mass transfer etc. As the knowledge of flow regime is of unique importance in understanding and analyzing two-phase flow, it is not surprising that a large volume of investigations have been carried-out to detect the flow regimes experimentally and to predict them theoretically. Theoretical predictions of flow regimes are essential for both the design as well as smooth and safe operations of plant equipment. Nevertheless, such predictions are difficult to make due to the complex nature of the flow phenomena. Further, the validity of these predictions should be rigorously tested against carefully conducted experiments.

Historically, identifications of flow regimes from experiments were first tried through visualization. Till today, visual observation, photography and videography play a very important role in identifying different regimes. One of the drawbacks of the visual technique is that the identification is grossly dependent on subjective decisions. Secondly, visualization of the phase distribution in the central region of the conduit is difficult, if not impossible, even for a transparent pair of fluids. Therefore, researchers put efforts to develop techniques for objective identification of flow regimes. Such techniques essentially contain two steps. At first, one needs to adopt a measurement technique, which is sensitive to the phase distribution (preferably local). In the next step, one needs to fix objective criteria for specific flow regimes based on a large number of measurements recorded over a wide range of operating parameters. A flow regime map (generally two dimensional) can then be constructed using suitable dimensional or non-dimensional parameters as the coordinates.

As multiphase flow is characterized by the random fluctuation of the phase fraction and phase distribution both in space and time even under steady operating conditions, a time series of fluctuating parameters (hear-after called signal) can be obtained from the measurement. A large number of measurement techniques, namely pressure (Gourich et al., 2006; Xie et al., 2004; Zhang et al., 2010b; Letzel et al., 1997), conductivity (Fossa, 1998; Das et al., 2000; Jana et al., 2006; Manera et al., 2009), optical (Oriola et al., 2008; Hawkesa et al., 2000; Rahim et al., 2005), capacitance (Gamio et al., 2005; Ortiz-Alemán et al., 2005, Zhang et al., 2010a; Reinecke and Mewes, 1997), ultrasonic (Xu and Xu, 1997; Xu et al., 1997; Murakawa et al., 2005; Cramer et al., 2004), radiation attenuation (Jung et al., 2009; Elias and Ben-Haim, 1980; Harms and Laratta, 1973) can be used to derive the time series as a function of instantaneous phase fraction and phase distribution. As the nature of the signal varies with the existing flow regime, the recorded signal may be used for a better identification of the flow regime.

To improve the objectivity of the process of identification further, different processing techniques had been employed on the raw signals. This helps to extract features out of the raw signals, which bear a direct correlation with the flow regimes. The commonly used processing techniques are Probability Density Function (PDF)(Das et al., 2000, Jana et al., 2006, Jones and Zuber, 1974), Power Spectrum Density Function (PSDF)(Cai et al., 1996; Wang and Shoji., 2002; Li and Tomita, 2001), Signal-to-Noise (SN) ratio (Gillandt et al., 2001; Lübbert and Larson, 1990), Wavelet Transformation (Elperin and Klochko, 2002; Jana et al., 2008), Fractal analysis (Kozma et al., 1996; Jin et al., 2003), etc. The use of statistical parameters for the recognition of the pattern of phase distribution (Sekoguchi et al., 1987) and finally, for the classification of flow regimes reduces the arbitrariness substantially. However, the process is not fully objective, as the rule base is decided by the investigator.

It is a well-known fact that the occurrence of a particular flow regime depends on a large number of factors and the relationship between the two are highly nonlinear. Obviously, the success of the flow pattern identification depends on the correct non-linear mapping of the physical variables to the flow regimes. Accurate and objective prediction of flow regime is possible, only when the complex non-linear relationship can be explained in terms of basic physics and described in terms of mathematical formulation. As an alternative approach, application of different soft computing techniques had been tried to establish the relationship between the physical parameters and the flow regimes. The application of Artificial Neural Network (ANN) exhibits a definite promise in this regard. One of the earliest attempts of identifying flow regimes through the application of

ANN was made by Cai et al. (1994). The Kohonen's self-organizing neural network was applied by them to identify the flow regimes in a horizontal air-water flow. Stochastic features derived from turbulent absolute pressure signals obtained across a range of flow regimes, were used by them to train the network.

Most extensive application of ANN for the prediction of flow patterns from experimental results was made by Ishii and co-workers. A neuro-fuzzy methodology had been proposed by Mi et al. (1996) and Tsoukalas et al. (1997) to identify the flow regimes based on impedance signal of the void fraction. In that investigation, the filtering and interpolative capabilities of neural networks had been combined with the representational advantages of fuzzy systems for the purpose of mapping idiosyncratic area-averaged impedance measurements to multiphase flow regimes. Multi-layer artificial neural network approach had been used by Mi et al. (1998) to identify flow regimes using signals extracted from non-intrusive impedance measurements. Flow regime identification carried out by instrumental indicators may include instrumentation errors. To avoid any instrumentation error and any subjective judgment involved, vertical flow regime identification was performed by Mi et al. (2001) based on theoretical two-phase flow simulation with supervised and self-organizing neural network systems. The networks were trained with the results from an idealized simulation that was mainly based on Mishima and Ishii's (1984) flow regime map, the drift flux model, and the newly developed model of slug flow. It had been concluded by them that the neural network systems are appropriate classifiers of vertical flow regimes. For the vertical upward and downward co-current two-phase flow pattern during rapid transients, an instantaneous and objective flow regime identification method had been proposed by Lee et al. (2008). The design of the neural network fed by the preprocessed impedance signals of the cross-sectional void fraction had been suggested by them to satisfy the requirement of both objective and an instantaneous identification. For the preprocessing, a feed-forward and a self-organized neural network were tested using the experimental data as objective reasoning engines. It had been found that the flow regime identifier, proposed by them could successfully identify the flow regime using the short-term observation data within 1 s. To identify both global (traditionally, the flow regimes in two-phase flow are considered in a global sense) and local flow regimes (a local flow regime is required to understand and model the interfacial structures present in the flow) in a two-phase upward flow, a new approach based on self-organized neural network had been proposed by Julia et al. (2008). The bubble chord length distributions measured simultaneously with three double-sensor conductivity probes, had been fed to the network. The results obtained by them for global flow regime identification reasonably agreed with the visual observation for all the flow conditions. But, the results correspond to the local flow regime identification agreed with the global ones only when measured at the center of the pipe. Radial and axial flow regimes development in adiabatic upward air-water two-phase flow in a vertical annulus had been analyzed by Julia et al. (2011), where local flow regimes had been identified using conductive probe and neural network. The local flow regime was characterized by the void fraction and bubble chord length. The flow regime indicator had been chosen as some statistical parameters of local bubble chord length distributions and self-organized neural networks had been used for the mapping. They reported that the radial flow regime transition was always initiated at the center of the flow channel and then propagated towards the channel boundaries. The axial development of flow regime was governed by superficial liquid velocity and radial location.

While Ishii and co-workers used different statistical features extracted from the signals of conductivity probes, Sharma et al. (2006) used the basic operating variables like phase superficial velocities, pipe diameter and pipe inclination as input parameters. They extracted 4000 data points from some published flow pattern maps. Three different types of ANN, namely feed-forward back-propagation network, radial basis function network and probabilistic neural network with radial basis function were tried and the best prediction was achieved through the third option.

Presently, neuro-fuzzy inference systems have been gaining popularity in its capability for solving both the prediction and classification problems. The capabilities of neuro-fuzzy inference system for identification of flow regimes and forecasting liquid holdup in horizontal multiphase flow have extensively been investigated by Sebakhy (2010). A probabilistic mapping of adiabatic horizontal two-phase flow had been made by Canière et al. (2009) by capacitance signal feature clustering.

Gao and Jin (2009) proposed the application of complex network for the identification of flow pattern and characterization of nonlinear dynamics of co-current gas liquid up-flow through circular tube. Signals obtained from a multi-electrode array of conductance sensors had been used to construct three types of network, namely Flow Pattern Complex Network (FPCN), Fluid Dynamic Complex Network (FDCN) and Fluid Structure Complex Network (FSCN). The FPCN, constructed based on time delay embedding and modularity, was used as a unique flow pattern identification method. Statistical characteristics of FDCNs indicate that both the power law exponent and network entropy can characterize the non-linear dynamics of the flow phenomena.

Finally, it has been demonstrated that FSCN can effectively indicate the bubble coalescence and bubble collapse in gas-liquid flow.

On the other hand, Counter-current gas-liquid two-phase flow is a special kind of two-phase flow, where the two phases move in opposite directions. In a vertical counter-current gas-liquid two-phase flow, the liquid flows down and the gas flows upwards through the tube. In many industrial systems or devices, such as compact reflux condensers, desiccant cooling systems, nuclear reactor, petroleum and biomedical processing system, and others, counter-current gas-liquid two-phase flow is often encountered.

Over the years, various hydrodynamic aspects of counter-current flow had been investigated. A brief literature review is presented here on the studies carried out in the field of counter-current gas-liquid two-phase flow. Flooding phenomenon is considered as one of the most significant components of this field of research. Several attempts were made to investigate the flooding phenomenon in counter-current gas-liquid two-phase flow. Most of those studies were experimental ones. When the relative velocity of a falling liquid film to a counter-current gas reaches a certain value, a wave occurring on the film surface becomes unstable, its amplitude quickly increases, and thus, bridging the test tube and flooding occurs.

Several attempts had been made by various investigators to find out the factors affecting the flooding phenomenon experimentally. The effect of liquid properties on flooding had been studied by Imura et al. (1977) by varying the test section and test liquid. Experimental investigation was carried out by Suzuki and Ueda (1977) on flooding gas velocity in circular tubes with varying tube diameters, tube lengths, liquid flow rates, liquid viscosities and surface tensions. A similar investigation was conducted by them for annuli and rod bundles (Ueda and Suzuki, 1978). An experimental study had been made by O'Brien et al. (1986) to see the effect of liquid flow rate on flooding in a vertical annular counter-current two-phase flow. The effects of liquid properties and inclination angle of channel on flow patterns, counter-current flow limitation (that is, flooding), and gas hold-up (that is, void fraction) in counter-current two-phase flow had been experimentally investigated by Ghiaasiaan et al. (1997). The effect of the liquid properties had been studied by varying the combination of two phases (for example, air-demineralized water, air-mineral oil, air-paraffinic oil) and that of inclination was studied by varying the inclination angle of the channel (for example, $0^0$, $30^0$, $68^0$). Moreover, the influences of pipe inclination, pipe length, pipe diameter and surface tension of the working liquid on the onset of flooding of gas-liquid adiabatic counter-current two-phase flow in inclined pipes had been experimentally investigated by Ousaka et al. (2006). More recently, the effects of surface tension on flooding phenomenon in counter-current two-phase flow in an inclined tube was experimentally investigated by Deendarlianto et al. (2010).

Attempts were made to capture liquid film characteristics during flooding by some researchers. An experimental investigation of liquid film behavior at the onset of flooding during adiabatic counter-current air-water two-phase flow in an inclined pipe had been made by Deendarlianto et al. (2005). Trials were also made to determine the liquid film characteristics and study flooding phenomenon of counter-current gas-liquid flow in a vertical narrow channel with 10 mm gap by Drosos et al. (2006). Moreover, the problems related to free flowing liquid layer characteristics, counter-current gas-liquid two-phase flow and incipient flooding in small diameter inclined tubes had been experimentally studied by Pantzali et al. (2008).

Experimental study on air-water counter-current two-phase flow (on the onset of flooding and slugging) in vertical to horizontal pipes containing orifice type obstructions had been conducted by Teyssedou et al. (2005). Experimental studies on air-water counter-current two-phase flow limitation in a horizontal rectangular channel connected to an inclined riser had been conducted by Deendarlianto et al. (2008).

Several attempts were also made by various investigators to model and analyze the flooding phenomenon analytically. The effect of vapour condensation on counter-current flow limiting (CCFL) phenomenon had been analyzed through employing an analytical model by Tien (1977). Mathematical model was derived by Asahi (1978) to define the flooding and flow reversal conditions of two-phase annular flow. Flooding phenomenon in vertical counter-current gas-liquid two-phase flow under an electric field for both adiabatic as well as non-adiabatic cases were studied theoretically by Revankar and Chang (1984a,b). In a nuclear power plant, the possibility of hot leg flooding during reflux condensation cooling after a small-break loss-of-coolant accident had been predicted by Jeong (2002). To predict counter-current flow limitations during hot leg injection in the pressurized water reactors, a one-dimensional model had been proposed by Gargallo et al. (2005). A numerical investigation of the gas-liquid wavy interface on the onset of flooding in counter-current two-phase flows had been made by Trifonov (2010) using the Navier-Stokes equations.

Experimental investigation on flooding and then theoretical analysis on the generated experimental results had also been attempted by some researchers. An attempt was first made by McQuillant and Whalley (1985) to study the flooding phenomenon in vertical counter-current air-water two-phase flow experimentally and then, a simple theoretical model was presented. In this connection, the studies of Ragland et al. (1989a,b) and Tso et al. (1988) are worth mentioning.

Moving interface generated by counter-current gas-liquid stratified flow had been experimentally and theoretically investigated by Boyadjiev et al. (1976). To investigate the initiation conditions of liquid ascent, experimental study on the counter-current two-phase flow of air and water in vertical pipe was conducted by Koizumi and Ueda (1996). The flow structure in a thin, wavy falling liquid film in a vertical tube both with and without interfacial shear induced by a counter-current flow of gas had been investigated by Karimi and Kawaji (1999, 2000). Experimental investigation about local axial velocities inside the gas phase during counter-current two-phase flow in a vertical rectangular channel was carried out by Lioumbas et al. (2002). The flow structure around a bubble in air-water counter-current bubbly flow had experimentally been studied by Suzuki et al. (2002). Ultrasonic Velocity Profile monitor was employed by them to measure velocity profiles around a bubble. Experimental study on the pressure drop for two-phase counter-current flow in a packed column with a novel internal had been conducted by Han et al. (2003). The characteristics of counter-current bubbly flow in circular pipe had been investigated by Fuangworawong et al. (2007) using wire mesh tomography (WMT).

A discrete mathematical model and an iterative algorithm for its solution for the counter-current flow of dispersed and continuous phase had been proposed by Jiřičný et al. (1979a,b). Gas-liquid counter-current flow in laminar boundary layers with flat phase boundary had been theoretically analyzed (velocity distribution as well mass transfer kinetics) by Boyadjiev and Doichinova (2000) and Doichinova and Boyadjiev (2000) using similarity variables method. One, two and three-dimensional solutions for counter-current steady-state two-phase immiscible subsurface flow had been analytically derived by Tracy (2008). Experimental and numerical investigations on counter-current stratified flows in horizontal channels were made by Wintterle et al. (2008).

Some attempts were also made by the researchers to investigate the flow patterns of gas-liquid counter-current two-phase flow. Flow pattern transitions and pressure drop in vertical counter-current gas-liquid two-phase flow had theoretically been modelled by Taitel and Barnea (1983) from a mechanistic point of view. They showed that unlike the case of co-current flow, the situations of "no solution" and "multiple solutions" exit for counter-current gas-liquid two-phase flow. Experimental investigations for flow pattern, void fraction and slug rise velocity on counter-current two-phase flow in a vertical round tube with wire-coil inserts had been made by Kim et al. (2001) by varying the wire-coil diameter and coil pitches. Disturbances into the flow, was generated through the presence of wire-coil in the tube and as a result, the shape and motion of gas slug or bubbles in a wire-coil inserted tube were quite different from those observed in a smooth tube without the insertion. They showed that slug-rise velocity in wire-coil inserted tube was higher than that in the smooth tube. Though only slug, churn and annular flows appeared in smooth tube without wire-coil inserts within the test range covered by them, bubbly flow was also seen to appear in the tube with wire-coil inserts within the same test range of experiments. Theoretical and experimental investigations on horizontal counter-current gas-liquid two-phase flow were made by Wang and Kondo (1990) to characterize the flow patterns. They had also proposed a theoretical criterion for the onset of slug flow.

## 1.5 Gaps in the Literature and Motivation behind the Selection of Problems

The gaps in the literature obtained through detailed literature survey and the motivation behind the selection of the problems are stated below.

- Optimization of diffuser had been attempted by a few investigators using various methods like gradient-based techniques, direct search techniques etc. Techniques based on gradient search and direct search are powerful methodologies of optimization (Pratihar, 2008). But, in direct search method, the search starts with a randomly generated initial solution and the final optimal solution might depend on the chosen initial solution. The gradient-based method cannot be applied for a problem involving discontinuous objective function. Moreover, the chance of the gradient-based method for getting stuck at the local extremum is more. The optimization algorithms based on evolutionary principle can eliminate some of the difficulties listed above, as they work on a methodology different from those of classical techniques. For instance, Genetic Algorithm (GA), which loosely mimics genetic evolution following the principle of natural selection (Holland, 1975; Goldberg, 1989) offers a number of unique flexibilities. The gradient of the objective function with respect to its arguments is not required during optimization through the GA and that is why, they can also operate on irregular functions and those that are not differentiable. A GA starts its search from a population of solutions and not from a single parameter set. The set of initial guessed solutions has a low incidence on the set of final obtained optimum solutions due to the probabilistic nature of the GA. It searches solutions from all over the place within the feasible domains and never converges to a local optimum if it is handled appropriately and carefully. That is why, a GA is considered to be a robust optimization tool. Moreover, after reaching the convergence, the users get a population of individual solutions, many of which produce alternative to the best individual of the population. Not just one optimal solution is produced by GA but a collection of good solutions is produced by GA. From the design point-of-view, it may be useful to have a collection of alternative optimal solutions. No study has been reported using the GA to solve the said problem. Further, to the best of the author's knowledge, a hybrid computing scheme has not yet been developed, where commercial CFD software is used for hydrodynamics computation and a GA is utilized as a search and optimization tool. The use of a GA coupled with a CFD-based modelling possesses enough promise to solve shape optimization of systems involving fluid flow.

- The accommodation of a large number of streams in a single envelope presents a unique complexity to the designer. With the increase in number of streams, the option of arranging the streams also increases. The specific arrangement of various streams is known as stacking pattern in case of a plate-fin heat exchanger. It is obvious that all stacking patterns will not provide the same thermal performance. The best thermal performance can be obtained by a particular stacking pattern or at the best by a limited number of patterns. Again, all theoretically possible stacking patterns may not be practically viable due to the process constraints. This constitutes a unique optimization problem for multi-stream heat exchangers, which does not have a counterpart in case of a two-stream heat exchanger. Not much work has been reported on optimization of the plate-fin heat exchanger. Annual operating cost or weight had been optimized in a very limited number of papers. The need for optimizing the stacking pattern in a plate-fin heat exchanger has been appreciated by a number of researches. Time to time, some rules of thumb or broad design guide lines have been suggested. However, to the best of the author's knowledge, till date no algorithm for determining the optimum stacking pattern has been reported in the literature. This has motivated the present investigation. The methodology for optimization needs to be selected based on the nature of the problem. The present case involves optimization of a combinatorial problem and the classical derivative-based algorithms may not be suitable to solve it. One can think of applying a direct search technique, which becomes too much tedious for a large parameter space. On the other hand, gradient-based search requires the estimation of derivative and has a risk of getting stuck at a local extremum. A GA is a generic and robust search technique, which generally does not suffer from the above limitations. It provides several near-optimal solutions, which offer the designer a sufficient flexibility.

- It is clear from the literature survey in section 1.4.3 that inverse problems are encountered in many heat conduction situations, when severe working conditions make the measurement of thermal properties of unknown boundary conditions difficult. Several attempts had been made to solve the inverse heat conduction problem. Among them, some problems are related to inverse estimation of the boundary conditions. However, not much work has been reported on inverse estimation of the boundary conditions using the principle of soft computing (Pratihar, 2008).
- A wide range of experimental studies had been conducted on flooding and flow limitations in counter-current gas-liquid two-phase flow. To the best of the author's knowledge, no such study was found to deal with the development of a methodology for automatic flow-regime identification, classification or prediction of vertical counter-current two-phase flow based on objective description of the flow. However, prediction of flow regime is a prime issue in multiphase flow analysis. To capture the hydrodynamics of counter-current two-phase flow, mathematical modelling is really difficult. Though soft computing-based techniques are now being used by the researchers in the field of multi-phase flow, till date no effort has been made to capture the non-linear complex hydrodynamics of counter-current two-phase flow through soft computing-based approaches. The literature review reveals that, so far, the application of NN for the mapping of flow-regimes has been limited only to co-current gas-liquid flow. Counter-current gas-liquid flow, on the other hand, finds many important engineering applications. At this point, it should be mentioned that non-linearity exiting in counter-current two-phase flow is much more compared to that in co-current flow. Moreover, unlike the case of co-current two-phase flow, the situations of "no solution" and "multiple solutions" exist for counter-current gas-liquid two-phase flow.

## 1.6 Aims and Objective

Based on the above observations, the aims and objective of the present thesis have been set as follows:

- Attempts will be made to obtain optimal shape of the systems involving fluid flow (2D symmetric diffusers and nozzle). Hybrid computing scheme will be developed for the said optimization using commercial tool named Gambit for the shape construction and mesh generation, CFD tool (that is, Fluent) for carrying out hydrodynamic analysis, and employs a Genetic Algorithm (GA) for optimization. In the developed hybrid computing scheme, the GA, Gambit and Fluent (for CFD simulation) will be combined each other seamlessly, so that data transfer can take place automatically without any manual intervention. A number of alternate methodologies will be used to generate the optimum profiles. A comparison of all the methods will also be made. Finally, a comprehensive investigation will be carried to explore the effect of different design parameters on the optimum shape.

- A methodology will be developed for determining the optimum stacking pattern of parallel flow multi-stream plate-fin heat exchangers. No real design problem to find out the heat exchanger specifications will be attempted, but the simulation problem in order to study the effect of layer stacking pattern will be attempted. Efforts will also be made to check the validity of the solutions obtained from the proposed methodology.
- An inverse method will be proposed for estimating the boundary conditions in a heat conduction problem using regression analysis, neural network trained by a local optimizer (neural network with back-propagation algorithm) and lastly, that trained by the local and global optimizers simultaneously (that is, a GA-tuned neural network with back-propagation algorithm).
- The observations made through literature review and gaps in literature, leave a scope for further investigation on the flow patterns and their transitions during counter-current gas-liquid flow. Particularly, the applications of objective techniques for the identification of flow regimes have not yet been tried for counter-current flow. An attempt will be made to capture the highly complex nonlinear relationship between the developed flow regime and the input parameters (process variables) for vertical gas-liquid counter current two phase flow using soft computing based methodologies. An extensive experimentation will be conducted to detect the flow regimes during counter-current two-phase up flow through a vertical tube using air and water as the test fluids covering a wide range of phase velocities. A suitable methodology will be developed in order to classify the flow-regimes based on objective descriptions. Another aim of this study is to develop methodologies for fast and automatic identification and prediction of the flow regimes based on statistical features of the objective descriptions.

## 1.7 Contributions Made by the Scholar

- A hybrid computing scheme has been indigenously developed by combining two commercial softwares, namely Gambit (for shape construction and mesh generation) and Fluent (for carrying out hydrodynamic analysis) with the optimization tool (GA) seamlessly by using some specially designed system commands in C platform for the optimization of duct shapes. The interface among GA, Gambit and Fluent has been created in such a manner that the data transfer takes place between them in a fully automated way without any manual intervention. The developed methodology is generic in nature and is not restricted to the optimization of duct shapes only. The optimization of diverse thermo-fluids devices can be done readily with a suitable modification of the CFD simulation. For example, problems involving augmentation of heat transfer, design of chemical reactors, aerofoil shape in a cascade etc. can be solved using the similar methodology. The techniques used for combining Fluent with the indigenously developed optimization algorithm can also be utilized in principle in other applications like combining two altogether different commercial softwares.

- Though some broad design guide lines have been suggested for achieving a better stacking pattern, no algorithm for determining the optimum stacking pattern has been reported in the literature. A basic algorithm for searching the optimum stacking pattern in a MSPFHE has been developed by combining numerical simulation (for analysis of MSPFHE) with a GA (for optimization). The information about stacking pattern has been coded into the GA-string in a more efficient way.
- Methodologies have been developed for inverse estimation of boundary conditions using the principle of soft computing. The problem solved here, represents many problems of the same category even from the domain other than heat transfer. A hybrid optimization scheme has been developed by coupling the global search capability of the GA with the local search power of BP algorithm.
- No such study is found in the literature to deal with automatic flow-regime classification or prediction of counter-current two-phase flow based on objective descriptions. An extensive experimental investigation has been made for vertical air-water counter-current two-phase flow. The highly complex nonlinear relationship between the developed flow regime and the input parameters (process variables) for vertical gas-liquid counter-current two-phase flow has been captured using soft computing-based methodology. An elaborate scheme of measurements has been designed using two conducting probes. The methodologies have been developed for automatic classification and prediction of flow regimes based on the objective description. The modified clustering techniques coupled with GA have been established. Each individual dimension of the centers of hidden neurons in RBFNN has been updated separately using the back propagation algorithm.

## 1.8 Organization of the Thesis

The present dissertation has been organized in six chapters. Chapter 1 (that is, the present chapter) introduces the problems studied in this thesis. An extensive literature survey is carried out on the problems in order to define the aims and objective of the present thesis. Chapter 2 concentrates on the problem of duct shape optimization, which includes a detailed mathematical formulation of the problem and a discussion on the developed hybrid computing methodologies. The obtained results are stated and discussed here. Chapter 3 deals with the problem of stacking pattern optimization of multi-stream plate-fin heat exchanger. Chapter 4 focuses on the problem related to inverse estimation of boundary in heat conduction. Chapter 5 deals with the problems on diagnosis of counter-current two-phase flow. It describes the experimental setup, explains the designed scheme of measurements using conducting probes, methodologies developed for flow regime classification and prediction. Results have been stated and explained. Chapter 6 summarizes the important findings and conclusions made from the present study. The scope for future work has also been described in this chapter.

## 1.9 Summary

At first, a general introduction is given to thermo-fluid engineering problems. The concept of soft computing has been discussed in brief. The reasons behind the application of soft computing for solving complex real-life thermo-fluid problems have been explained. A thorough literature survey has been made on the thermo-fluid problems studied in this thesis. The gaps in the literature have been identified. The aims and objective of the present thesis have been stated. Contributions made by the scholar have been described. At last, an organization of the present dissertation has been included.

Anand, B., Jeyakumar, A.E., 2009. Fuzzy logic based load frequency control of hydro-thennal system with non-linearities. Intematioml Jourml of Electrical and Power Engineering 3, 112-118.

Asahi, Y., 1978. Flooding and flow reversal of two-phase annular flow. Nuclear Engineering and Design 47, 251-256.

Aulds, D.D., Barron, R.F., 1967. Three-fluid heat exchanger effectiveness. International Journal of Heat and Mass Transfer 10, 1457-1462.

Bängtsson, E., Noreland, D., Berggren, M., 2003. Shape optimization of an acoustic horn. Computer Methods in Applied Mechanics and Engineering 192, 1533-1571.

Baysal, O., Eleshaky, M., 1992. Aerodynamic design optimization using sensitivity analysis and computational fluid dynamics. AIAA Journal 30, 718-725.

Beck, J.V., 1970. Nonlinear estimation applied to the nonlinear inverse heat conduction problem. International Journal of Heat and Mass Transfer 13, 703-716.

Boyadjiev, Chr., Doichinova, M., 2000. Opposite-current flows in gas-liquid boundary layers-I. Velocity distribution. Int. J. Heat and Mass Transfer 43, 2701-2706.

Boyadjiev, Chr., Mitev, Pl., Beshkov, V., 1976. Laminar boundary layers at a moving interface generated by counter-current gas-liquid stratified flow. Int. J. Multiphase Flow 3, 61-66.

Cabuk, H., Modi, V., 1992. Optimum plane diffusers in laminar flow. Journal of Fluid Mechanics 237, 373-393.

Cai, S., Toral, H., Qiu, J., Archer, J.S., 1994. Neural network based objective flow regime identification in air-water two phase flow. Can. J. Chem. Eng. 72, 440-445.

Cai, Y., Wambsganss, M.W., Jendrzejczyk, J.A., 1996. Application of chaos theory in identification of two-phase flow patterns and transitions in a small, horizontal, rectangular channel. Energy Technology Division, Argonne National Laboratory, Argonne, Illinois 60439.

Canière, H., Bauwens, B., T'Joen, C., Paepe, M.D., 2009. Probabilistic mapping of adiabatic horizontal two-phase flow by capacitance signal feature clustering. International Journal of Multiphase Flow 35, 650-660.

Carlson, J.J., Johnston, J.P., Sagi, C.J., 1967. Effects of wall shape on flow regimes and performance in straight, two-dimensional diffusers. Journal of Basic Engineering 89, 151-160.

Cavazzuti, M., Corticelli, M.A., 2008. Optimization of heat exchanger enhanced surfaces through multiobjective genetic algorithms. Numerical Heat Transfer, Part A 54, 603-624.

Chamberlain, R.D., Lancaster, J.M., Cytron, R.K., 2008. Visions for application development on hybrid computing systems. Parallel Computing 34, 201-216.

Chato, J.C., Lverman, R.J., Shah, J.M., 1971. Analyses of parallel flow multi-stream heat exchangers. International Journal of Heat and Mass Transfer 14, 1691-1703.

Chen, H.T., Lin, S.Y., Fang, L.C., 2001. Estimation of surface temperature in two-dimensional inverse heat conduction problems. International Journal of Heat and Mass Transfer 44, 1455-1463.

Chen, H.T., Lin, S.Y., Wang, H.R., Fang, L.C., 2002. Estimation of two-sided boundary conditions for two dimensional inverse heat conduction problems. International Journal of Heat and Mass Transfer 45, 15-23.

Copiello, D., Fabbri, G., 2009. Multi-objective genetic optimization of the heat transfer from longitudinal wavy fins. International Journal of Heat and Mass Transfer 52, 1167–1176.

Cortes, O., Urquiza, G., Hernandez, J.A., Cruz, M.A., 2007. Artificial Neural Networks for Inverse Heat Transfer Problems. Electronics, Robotics and Automotive Mechanics Conference, Cuernavaca, Morelos, Mexico.

Cramer, A., Zhang, C., Eckert, S., 2004. Local flow structures in liquid metals measured by ultrasonic doppler velocimetry. Flow Measurement and Instrumentation 15, 145-153.

Das, G., Das, P.K., Purohita, N.K., Mitra, A.K., 2000. Phase distribution of gas-liquid mixtures in concentric annuli-inception and termination of asymmetry. International Journal of Multiphase Flow 26, 857-876.

Dash, P.K., Liew, A.C., Rahman, S., Dash, S., 1995. Fuzzy and neuro-fuzzy computing models for electric load forecasting. Engineering Applications of Artificial Intelligence 8, 423-433.

Davis, C.E., May, G.S., 2008. Neural network control of variable-frequency microwave processing of polymer dielectric curing. IEEE Transactions on Electronics Packaging Manufacturing 31, 104-113.

Deendarlianto, Ousaka, A., Indarto, Kariyasaki, A., Lucas, D., Vierow, K., Vallee, C., Hogan, K., 2010. The effects of surface tension on flooding in counter-current two-phase flow in an inclined tube. Experimental Thermal and Fluid Science, 34, 813-826.

Deendarlianto, Ousaka, A., Kariyasaki, A., Fukano, T., 2005. Investigation of liquid film behavior at the onset of flooding during adiabatic counter-current air-water two-phase flow in an inclined pipe. Nuclear Engineering and Design 235, 2281-2294.

Deendarlianto, Vallée, C., Lucas, D., Beyer, M., Pietruske, H., Carl, H., 2008. Experimental study on the air/water counter-current flow limitation in a model of the hot leg of a pressurized water reactor. Nuclear Engineering and Design 238, 3389-3402.

Deep, K., Das, K.N., 2008. Quadratic approximation-based hybrid genetic algorithm for function optimization. Applied Mathematics and Computation 203, 86-98.

Deng, S., Hwang, Y., 2006. Applying neural networks to the solution of forward and inverse heat conduction problems. International Journal of Heat and Mass Transfer 49, 4732-4750.

Deng, S., Hwang, Y., 2007. Solution of inverse heat conduction problems using Kalman filter-enhanced Bayesian back propagation neural network data fusion. International Journal of Heat and Mass Transfer 50, 2089-2100.

Desaix, M., Anderson, D., Lisak, M., 2005. The brachistochrone problem—an introduction to variational calculus for undergraduate students. European Journal of Physics 26, 857-864.

Díaz, G., Sen, M., Yang, K.T., McClain R.L., 2001a. Adaptive neurocontrol of heat exchangers. Journal of Heat Transfer 123, 556-562.

Díaz, G., Sen, M., Yang, K.T., McClain R.L., 2001b. Dynamic prediction and control of heat exchangers using artificial neural networks. International Journal of Heat and Mass Transfer 44, 1671-1679.

Díaz, G., Sen, M., Yang, K.T., McClain R.L., 2004. Stabilization of thermal neurocontrollers. Applied Artificial Intelligence 18, 447-466.

Dipama, J., Teyssedou, A., Sorin, M., 2008. Synthesis of heat exchanger networks using genetic algorithms. Applied Thermal Engineering 28, 1763-1773.

Doichinova, M., Boyadjiev, Chr., 2000. Opposite-current flows in gas-liquid boundary layers-II. Mass transfer kinetics. Int. J. Heat and Mass Transfer 43, 2707-2710.

Dora, J.D., Maignan, A., Ruse, M.M., Yovine, S., 2001. Hybrid Computation. International Conference on Symbolic and Algebraic Computation, Ontario, Canada.

Drosos, E.I.P., Paras, S.V., Karabelas, A.J., 2006. Counter-current gas-liquid flow in a vertical narrow channel-liquid film characteristics and flooding phenomena. Int. J. Multiphase Flow 32, 51-81.

Duda, P., Taler, J., 2009. A new method for identification of thermal boundary conditions in water-wall tubes of boiler furnace. International Journal of Heat and Mass Transfer 52, 1517-1524.

Dulikravich, G.S., 1992. Aerodynamic shape design and Optimization: status and trends. AIAA Journal of Aircraft 29, 1020-1026.

Duran, O., Rodriguez, N., Consalter, L.A, 2009. Neural networks for cost estimation of shell and tube heat exchangers. Expert Systems with Applications 36, 7435-7440.

Elias, E., Ben-Haim, Y., 1980. Determination of spatial distribution in two-phase flow using scattered gamma radiation. Nuclear Engineering and Design 59, 433-441.

Elperin, T., Klochko. M., 2002. Flow regime identification in a two-phase flow using wavelet transform. Experiments in Fluids 32, 674-682.

Fabbri, G., 1998. Heat transfer optimization in internally finned tubes under laminar flow conditions. International Journal for Heat and Mass Transfer 41, 1243-1253.

Fabbri, G., 2000. Heat transfer optimization in corrugated wall channels. International Journal for Heat and Mass Transfer 43, 4299-4310.

Fabbri, G., 2004. Effect of viscous dissipation on the optimization of the heat transfer in internally finned tubes. International Journal for Heat and Mass Transfer 47, 3003-3015.

Fadare, D.A., Fatona, A.S., 2008. Artificial Neural Network Modeling of Heat Transfer in a Staggered Cross-flow Tube-type Heat Exchanger. The Pacific Journal of Science and Technology 9, 317-323.

Falco, I.D., 1997. An introduction to evolutionary algorithms and their application to the aerofoil design problem-part I: the algorithms. Von Kármán lecture series on fluid dynamics, Von Kareman Institute, Rhode-Saint-Genese, Bruxelles, Belgium.

Fan, H.Y., Dulikravich, G.S., Han, Z.X., 2005. Aerodynamics data modeling using support machines. Inverse Problem in Science and Engineering 2005, 13, 261-278.

Fan, Y.N., 1966. How to design plate fin heat exchangers. Hydrocarbon Process 45, 211-217.

Fang, Z., Xie, D., Diao, N., Grace, J.R., Lim, C.J., 1997. A new method for solving the inverse conduction problem in steady heat flux measurement. International Journal of Heat and Mass Transfer 40, 3947-3953.

Fieg, G., Luo, X., Jeżowski, J., 2009. A monogenetic algorithm for optimal design of large-scale heat exchanger networks. Chemical engineering and processing 48, 1506-1516.

Fluent Inc., 2006a. 'FLUENT 6.3 User's Guide'.

Fluent Inc., 2006b. 'GAMBIT 2.3 User's Guide'.

Fossa, M., 1998. Design and performance of a conductance probe for measuring the liquid fraction in two-phase gas-liquid flows. Flow Measurement and Instrumentation 9, 103-109.

Fuangworawong, N., Kikura, H., Aritomi, M., Komeno, T., 2007. Tomographic imaging of counter-current bubbly flow by wire mesh tomography. Chemical Engineering Journal 130, 111-118.

Gamio, J.C., Castro, J., Rivera, L., Alamilla, J., Garcia-Nocetti, F., Aguilar, L., 2005. Visualisation of gas-oil two-phase flows in pressurised pipes using electrical capacitance tomography. Flow Measurement and Instrumentation 16, 129-134.

Gao, Z., Jin, N., 2009. Flow-pattern identification and nonlinear dynamics of gas-liquid two-phase flow in complex networks. Physical Review E 79, 066303-1-- 066303-14.

Gargallo, M., Schulenberg, T., Meyer, L., Laurien, E., 2005. Counter-current flow limitations during hot leg injection in pressurized water reactors. Nuclear Engineering and Design 235, 785-804.

Ghiaasiaan, S.M., Wu, X., Sadowski, D.L., Abdel-Khalik, S.I., 1997. Hydrodynamic characteristics of counter-current two-phase flow in vertical and inclined channels: Effects of liquid properties. Int. J. Multiphase Flow 23, 1063-1083.

Ghosh, I., Sarangi, S.K., Das, P.K., 2006. An alternate algorithm for the analysis of multi-stream plate fin heat exchangers. International Journal of Heat and Mass Transfer 49, 2889-2902.

Ghosh, S., Das, K.C, Mookherjee, S., Sanyal, D., 2005. Design and simulation of a fuzzy logic controller for velocity tracking of a hydraulic actuation system. Proc. 32nd National Conference on Fluid Mechanics and Fluid Power, Osmanabad, India, pp. E3-1-E3-10.

Gillandt, I., Fritsching, U., Bauckhage, K., 2001. Measurement of phase interaction in dispersed gas/particle two-phase flow. International Journal of Multiphase flow 27, 1313-1332.

Goel, T., Dorney, D.J., Haftka, R.T., Shyy, W., 2007. Improving the hydrodynamic performance of diffuser vanes via shape optimization. The 43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Cincinnati, OH.

Goldberg, D.E., 1989. Genetic Algorithms in Search, Optimization and Machine Learning. Addison-Wesley Longman Publishing Co., Inc. Boston, MA, USA.

Gosselin, L., Tye-Gingras, M., Mathieu-Potvin, F., 2009. Review of utilization of genetic algorithms in heat transfer problems. International Journal of Heat and Mass Transfer 52, 2169-2188.

Gourich, B., Vial, C., Essadki, A.H., Allam, F., Soulami, M.B., Ziyad, M., 2006. Identification of flow regimes and transition points in a bubble column through analysis of differential pressure signal-influence of the coalescence behavior of the liquid phase. Chemical Engineering and Processing 45, 214-223.

Han, M., Lin, H., Yuan, Y., Wang, D., Jin, Y., 2003. Pressure drop for two phase counter-current flow in a packed column with a novel internal. Chemical Engineering Journal 94, 179-187.

Han, S.Y., Maeng, J.S., 2003. Shape optimization of cut-off in a multi-blade fan/scroll system using neural network. International Journal for Heat and Mass Transfer 46, 2833-2839.

Hara, H., Bai, Q., Fujita, Y., 1999. Application of neural network to inverse heat conduction problems. Mem Grad Sch Eng Kyushu Univ 59, 137-154.

Harms, A.A., Laratta, F.A.R., 1973. The dynamic-bias in radiation interrogation of two-phase flow. International Journal of Heat and Mass Transfer 16, 1459-1465.

Haseler, L., 1983. Performance calculation methods for multi-stream plate fin heat exchangers. in: Taborek, J., Hewitt, G.F., Afgan, N., (Eds.), Heat Exchangers-Theory and Practice. Hemisphere Publishing, New Work, 495-506.

Hawkesa, N.J., Lawrenceb, C.J., Hewitt, G.F., 2000. Studies of wispy-annular flow using transient pressure gradient and optical measurements. International Journal of Multiphase Flow 26, 1565-1582.

Hilbert, R., Janiga, G., Baron, R., Thévenin, D., 2006. Multi-objective shape optimization of a heat exchanger using parallel genetic algorithms. International Journal of Heat and Mass Transfer 49, 2567-2577.

Holland, J.H., 1975. Adaptation in Natural and Artificial systems. The University of Michigan press, Ann Arbor, MI, USA.

Howard, F.G., 1968. Single-thermocouple method for determining heat flux to a thermally thick wall. NASA TND473.

Hsu, P.T., 2006. Estimating the boundary condition in a 3D inverse hyperbolic heat conduction problem. Applied Mathematics and Computation. 177, 453-464.

Hsu, P.T., 2008. The inverse estimation of the thermal behavior and the viscosity of fluid between two horizontal concentric cylinders with rotating inner cylinder. Applied Thermal Engineering 28, 380-387.

Hsu, P.T., Chu, Y.H., 2004. An inverse non-Fourier heat conduction problem approach for estimating the boundary condition in electronic. Applied Mathematical Modelling 28, 639-652.

Hsu, P.T., Wang, S.G., Li, T.Y., 2000. An inverse problem approach for estimating the wall heat flux in flimwise condensation on a vertical surface with variable heat flux and body force convection. Applied Mathematical Modelling 24, 235-245.

Hsu, P.T., Yang, Y.T., Chen, C.K., 1998. Simultaneously estimating the initial and boundary conditions in a two dimensional hollow cylinder. International Journal of Heat and Mass Transfer. 41, 219-227.

Hwang, Y., Deng, S., 2008. Applying Neural Networks to the Solution of the Inverse Heat Conduction Problem in a Gun Barrel. Journal of Pressure Vessel Technology. 130, 031203-1--031203-8.

Imura, H., Kusuda, H., Funatsu, S., 1977. Flooding velocity in a counter-current annular two-phase flow. Chemical Engineering Sciences 32, 79-87.

Islamoglu, Y., 2003. A new approach for the prediction of the heat transfer rate of the wire-on-tube type heat exchanger—use of an artificial neural network model. Applied Thermal Engineering 23, 243-249.

Islamoglu, Y., Kurt, A., Parmaksizoglu, C., 2005. Performance prediction for non-adiabatic capillary tube suction line heat exchanger: an artificial neural network approach. Energy Conversion and Management 46, 223-232.

Jana, A.K., Das, G., Das, P.K., 2006. Flow regime identification of two-phase liquid-liquid upflow through vertical pipe. Chemical Engineering Science 61, 1500-1515.

Jana, A.K., Das, G., Das, P.K., 2008. The hydrodynamics of liquid-liquid up-flow through a venturimeter. International Journal of Multiphase Flow 34, 1119-1129.

Jarny, Y., Ozisik, M.N., Bardon, J.P., 1991. A general optimization method using adjoint equation for solving multidimensional inverse heat conduction. International Journal of Heat and Mass Transfer 34, 2911-2919.

Jeong, H.Y., 2002. Prediction of counter-current flow limitation at hot leg pipe during a small-break LOCA. Annals of Nuclear Energy 29, 571-583.

Jin, N.D., Nie, X.B., Ren, Y.Y., Liu, X.B., 2003. Characterization of oil/water two-phase flow patterns based on nonlinear time series analysis. Flow Measurement and Instrumentation 14, 169-175.

Jiřičný, V., Krátký, M., Procházka, J., 1979a. Counter-current flow of dispersed and continuous phase-I. Chemical Engineering Sciences 34, 1141-1149.

Jiřičný, V., Krátký, M., Procházka, J., 1979b. Counter-current flow of dispersed and continuous phase-II. Chemical Engineering Sciences 34, 1151-1158.

Jones, O.C., Zuber, N., 1974. Statistical methods for measurement and analysis of two-phase flow. Proc. Int. Heat Transfer Conf., Tokyo.

Julia, J.E., Liu, Y., Paranjape, S., Ishii, M., 2008. Upward vertical two-phase flow local flow regime identification using neural networks techniques. Nuclear Engineering and Design 238, 156-159.

Julia, J.E., Ozar, B., Jeong, J.J., Hibiki, T., Ishii, M., 2011. Flow regime development analysis in adiabatic upward two-phase flow in a vertical annulus. International Journal of Heat and Fluid Flow 32, 164-175.

Jung, S.H., Kim, J.S., Kim, J.B., Kwon, T.Y., 2009. Flow-rate measurements of a dual-phase pipe flow by cross-correlation technique of transmitted radiation signals. Applied Radiation and Isotopes 67, 1254-1258.

Kao, S., 1961. A systematic design approach for a multi-stream exchanger with interconnected wall. ASME Paper 61-WA-255.

Karimi, G., Kawaji, M., 1999. Flow characteristics and circulatory motion in wavy falling films with and without counter-current gas flow. Int. J. Multiphase Flow 25, 1305-1319.

Karimi, G., Kawaji, M., 2000. Flooding in vertical counter-current annular flow. Nuclear Engineering and Design 200, 95-105.

Kays, W.M., London, A.L., 1984. Compact Heat Exchangers, third ed., McGraw-Hill, New York.

Kim, H.Y., Koyama, S., Matsumoto, W., 2001. Flow pattern and flow characteristics for counter-current two-phase flow in a vertical round tube with wire-coil inserts. Int. J. Multiphase Flow 27, 2063-2081.

Kline, S.J., Abbott, D.E., Fox, R.W., 1959. Optimum design of straight-walled diffusers. Journal of Basic Engineering 81, 321-329.

Koizumi, Y., Ueda, T., 1996. Initiation conditions of liquid ascent of the counter-current two-phase flow in vertical pipes (in the presence of two-phase mixture in the lower portion). Int. J. Multiphase Flow 22, 31-43.

Kozma, R., Kok, H., Sakuma, M., Djainal, D.D., Kitamura, M., 1996. Characterization of two-phase flows using fractal analysis of local temperature fluctuations. International Journal of Multiphase Flow 22, 953-968.

Kumar, R., Kaushik, S.C., Garg., S.N., 2006. Heating and cooling potential of an earth-to-air heat exchanger using artificial neural network. Renewable Energy 31, 1139-1155.

Kumar, R., Sinha, A.R., Sing, B.K., Modhukalya, U., 2008. A design optimization tool of earth-to-air heat exchanger using a genetic algorithm. Renewable Energy 33, 2282-2288.

Launder, B.E., Spalding, D.B., 1972. Lectures in Mathematical Models of Turbulence. Academic Press, London, England.

Launder, B.E., Spalding, D.B., 1974. The Numerical Computation of Turbulent Flows. Computer Methods in Applied Mechanics and Engineering 3, 269-289.

Lavelle, J.F., Bloor, C.M., Covell, J.W., 1973. A technique for processing coronary hemodynamic data with a small hybrid computing system. Computers in Biology and Medicine 3, 47-54.

Lecoeuche, S., Lalot, S., Desmet, B., 2005. Modelling a non-stationary single tube heat exchanger using multiple coupled local neural networks. International Communications in Heat and Mass Transfer 32, 913-922.

Lecoeuche, S., Mercère, G., Lalot, S., 2006. Evaluating time-dependent heat fluxes using artificial neural networks. Inverse Problems in Science and Engineering. 14, 97-109.

Lee, J.Y., Ishii. M., Kim, N.S., 2008. Instantaneous and objective flow regime identification method for the vertical upward and downward co-current two-phase flow. Int. J. Heat Mass Transf. 51, 3442-3459.

Lee, K.S., Kim, W.S., Si, J.M., 2001. Optimal shape and arrangement of staggered pins in the channel of a plate heat exchanger. International Journal for Heat and Mass Transfer 44, 3223-3231.

Lehnhauser, T., Schafer, M., 2005. A numerical approach for shape optimization of fluid flow domains. Computer Methods in Applied Mechanics and Engineering 194, 5221-5241.

Lethander, A.T., Thole, K.A., Zess, G., Wagner, J., 2004. Vane-Endwall junction optimization to reduce turbine vane passage adiabatic wall temperatures. Journal of Propulsion and Power 20, 1105-1116.

Letzel, H.M., Schouten, J.C., Krishna, R., Bleek C.M.V., 1997. Characterization of regimes and regime transitions in bubble columns by chaos analysis of pressure signals. Chemical Engineering Science 52, 4447-4459.

Li, H., Tomita, Y., 2001. Characterization of pressure fluctuation in swirling gas-solid two-phase flow in a horizontal pipe. Advanced Powder Technology 12, 169-185.

Liang, H., Huang, S., Bai, F.A., 2006. A hybrid algorithm for computing permanents of sparse matrices. Applied Mathematics and Computation 172, 708-716.

Liang, W.Y., Huang, C.C., 2008. A hybrid approach to constrained evolutionary computing: case of product synthesis. Omega 36, 1072-1085.

Lin, Z.C., Lin, V.H., 2005. Thermal conductivity investigation for upsetting with a procedure of combining inverse model and the proposed regularization of Tikhonov method. Journal of Material processing Technology. 167, 208-217.

Lioumbas, I.S., Mouza, A.A., Paras, A.V., 2002. Local velocities inside the gas phase during counter-current two-phase flow in a narrow vertical channel, Trans IChemE, 80, Part A, 667-673.

Lordanov, V.I., Steward, A.P., 1984. A method and a computer program for determining the thermal diffusivity in a solid slab. Applied Mathematical Modelling 8, 169-178.

Lübbert, A., Larson, B., 1990. Detailed investigations of the multiphase flow in airlift tower loop reactors. Chemical Engineering Science, 45, 3047-3053, 1990.

Luo, X., Li, K., Li, M., 2001. Prediction of the thermal performance of multi-stream plate fin heat exchangers. International Journal of Heat Exchangers 2, 47-60.

Luo, X., Li, M., Roetzel, W., 2002. A general solution for one dimensional multi-stream heat exchangers and their networks. International Journal of Heat and Mass Transfer 45, 2695-2705.

Luo, X., Wei, G.-F., Sun, Y.-Q., He, G.-H., Yao, P.-J., 2004b. Multi-stream heat exchanger networks synthesis with improved genetic algorithm. Dalian Ligong Daxue XuebaoJournal of Dalian University of Technology 44, 315-336.

Luo, X., Wen, Q.Y., Fieg, G., 2009. A hybrid genetic algorithm for synthesis of heat exchanger networks. Computers and Chemical Engineering 33, 1169-1181.

Luo, X., Yao, P., Wei, G., Roetzel, W., 2004a. Study on multi-stream heat exchanger network synthesis with parallel genetic/simulated annealing algorithm. Chinese Journal of Chemical Engineering 12, 66-77.

Ma, X., Yao, P., Luo, X., Roetzel, W., 2007. Synthesis of flexible multi-stream heat exchanger networks based on stream pseudo-temperature with genetic/simulated annealing algorithms. Journal of the Chinese Institute of Chemical Engineers 38, 321-331.

Ma, X., Yao, P., Luo, X., Roetzel, W., 2008. Synthesis of multi-stream heat exchanger network for multi-period operation with genetic/simulated annealing algorithms. Applied Thermal Engineering 28, 809-823.

Madsen, J.I., Shyy, W.R., Haftka, T., 2000. Response surface techniques for diffuser shape optimization. AIAA Journal. 38, 1512-1518.

Maeng, J.S., Han, S.Y., 2004. Application of the growth-strain method for shape optimization of flow systems. Numerical Heat Transfer, Part A 45, 235-246.

Maidi, A., Diaf, M., Corriou, J.P, 2008. Optimal linear PI fuzzy controller design of a heat exchanger. Chemical Engineering and Processing 47, 938-945.

Mäkinen, R., Neittaanmäki, P., Périaux, J., Toivanen, J., 1998. A genetic algorithm for multiobjective design optimization in aerodynamics and electromagnetics. Computational Fluid Dynamics '98, Proceedings of the ECCOMAS 98 conference, Papailiou, K.D., Tsahalis, D., Périaux, J., Knörzer, D., (Eds.), Wiley, Athens, Greece 2, 418-422.

Manera, A., Ozar, B., Paranjape, S., Ishii, M., Prasser, H.-M., 2009. Comparison between wire-mesh sensors and conductive needle-probes for measurements of two-phase flow parameters. Nuclear Engineering and Design 239, 1718-1724.

Marco, N., Désidéri, J.A., Lanteri, S., 1999. Multi-objective Optimization in CFD by Genetic Algorithm. Research Report, No. 3686, Institut National de Recherche en Informatique et en Automatique, France.

Matlab 7.1, 2005. MATLAB Software, Version 7.1, Release name R14SP3. [38]

Matos, R.S., Vargas, J.V.C., Laursen, T.A., Bejan, A., 2004. Optimally staggered finned circular and elliptic tubes in forced convection. International Journal for Heat and Mass Transfer 47, 1347-1359.

McQuillant, K.W., Whalley, P.B., 1985. Flooding in vertical two-phase flow. Int. J. Multiphase Flow 11, 741-760.

Mi, Y., Ishii, M., Tsoukalas, L.H., 1998. Vertical two-phase flow identification using advanced instrumentation and neural networks. Nuclear Engineering and Design 184, 409-420.

Mi, Y., Ishii, M., Tsoukalas, L.H., 2001. Flow regime identification methodology with neural networks and two-phase flow models. Nuclear Engineering and Design 204, 87-100.

Mi, Y., Tsoukalas, L.H., Ishii, M., Li, M., Xiao, Z., 1996. Hybrid fuzzy-neural flow identification methodology. Proc. 5th IEEE Int. Conf. on Fuzzy Systems, New Orleans, LA, in press.

Minitab14, 2004. Statistical Software, Available at http://www.gtpcc.org/gtpcc/minitab14.htm

Mishima, K., Ishii, M., 1984. Flow regime transition criteria for upward two-phase flow in vertical tubes. Int. J. Heat Mass Transf. 27, 723-737.

Mishra, M., Das, P.K., 2009. Thermoeconomic design-optimisation of crossflow platefin heat exchanger using genetic algorithm. International Journal of Exergy 6, 837-852.
Mishra, M., Das, P.K., Sarangi, S., 2004. Optimum design of crossflow plate-fin heat exchangers through genetic algorithm. International Journal of Heat Exchangers 5, 379-401.
Mohagheghi, M., Shayegan, J., 2009. Thermodynamic optimization of design variables and heat exchangers layout in HRSGs for CCGT, using genetic algorithm. Applied Thermal Engineering 29, 290-299.
Mohammadi, B., Molho, J., Santiago, J., 2003. Incomplete sensitivities for the design of minimal dispersion fluidic channels. Computer Methods in Applied Mechanics and Engineering 192, 4131-4145.
Mohammadi, B., Pironneau, O., 2001. Applied Shape Optimization for Fluids. Oxford University Press: Oxford.
Moon, J.W., Jung, S.K., Kim, J.J., 2009. Application of ANN (Artificial-Neural-Network) in residential thermal control. Eleventh International IBPSA Conference, Glasgow, Scotland, pp. 64-71.
Murakawa, H., Kikura, H., Aritomi, M., 2005. Application of ultrasonic doppler method for bubbly flow measurement using two ultrasonic frequencies. Experimental Thermal and Fluid Science 29, 843-850.
O'Brien, S.A., Such, D.K., Mills, A.F., 1986. The effect of liquid flow rate on flooding in vertical annular countercurrent two-phase flow. Int. J. Multiphase Flow 12, 699-704.
Okabe, T., Foli, K., Olhofer, M., Jin, Y., Sendhoff, B., 2003. Comparative studies on micro heat exchanger optimization. Proceedings of the IEEE Congress on Evolutionary Computation, Canberra, Australia 1, 647-654.
Oriola, J., Leclercc, J.P., Jallutb, C., Tochona, P., Clementa, P., 2008. Characterization of the two-phase flow regimes and liquid dispersion in horizontal and vertical tubes by using coloured tracer and non-intrusive optical detector. Chemical Engineering Science 63, 24-34.
Ortiz-Alemán, C., Martin, R., 2005. Inversion of electrical capacitance tomography data by simulated annealing: Application to real two-phase gas-oil flow imaging. Flow Measurement and Instrumentation 16, 157-162.
Ousaka, A., Deendarlianto, Kariyasaki, A., Fukano, T., 2006. Prediction of flooding gas velocity in gas-liquid counter-current two-phase flow in inclined pipes. Nuclear Engineering and Design 236, 1282-1292.
Özçelik, Y, 2007. Exergetic optimization of shell and tube heat exchangers using a genetic based algorithm. Applied Thermal Engineering, 27, 1849-1856.
Ozkol, I., Komurgoz, G., 2005. Determination of the optimum geometry of the heat exchanger body via a genetic algorithm. Numerical Heat Transfer, Part A, 48, 283-296.
Pacheco-Vega, A., Díaz, G., Sen, M., Yang, K.T., McClain, R.L., 2001a. Heat rate predictions in humid air-water heat exchangers using correlations and neural networks. Journal of Heat Transfer 123, 348-354.
Pacheco-Vega, A., Sen, M., Yang, K.T., McClain, R.L., 2001b. Neural network analysis of fin-tube refrigerating heat exchanger with limited experimental data. International Journal of Heat and Mass Transfer 44, 763-770.
Pacheco-Vega, A.J., 2002. Simulation of compact heat exchangers using global regression and soft computing. Ph.D thesis, University of Notre Dame, Indiana.
Padra, C., 2006. The beginnings of variational calculus, and its early relation with numerical methods. Variational Formulations in Mechanics: Theory and Applications, Taroco, E., de Souza Neto, E.A., Novotny, A.A., (eds). c CIMINE, Barcelona, Spain.
Paffenbarger, J., 1990. General computer analysis of multi-stream plate fin heat exchangers, in: Shah, R.K., Kraus, A.D., Metzger, D. (Eds.), Compact Heat

Exchangers -A Festschrift for London A.L., Hemisphere Publishing, New York, pp. 727-746.

Pantzali, M.N., Mouza, A.A., Paras, S.V., 2008. Counter-current gas-liquid flow and incipient flooding in inclined small diameter tubes. Chemical Engineering Science 63, 3966-3978.

Park, H.M., Chung, O.Y., Lee, J.H., 1999. On the solution of inverse heat transfer problem using the Karhunen_Loéve Galerkin method. International Journal of Heat and Mass Transfer 42, 127-142.

Park, H.M., Yoon, T.Y., 2001. Solution of inverse radiation problems using the Karhunen-Loéve Galerkin procedure. Journal of Quantitative Spectroscopy & Radiative Transfer 68, 489-506.

Peng, H., Ling, X., 2008. Optimal design approach for the plate-fin heat exchangers using neural networks cooperated with genetic algorithms. Applied Thermal Engineering 28, 642-650.

Peng, H., Ling, X., 2009. Neural networks analysis of thermal characteristics on plate-fin heat exchangers with limited experimental data. Applied Thermal Engineering 29, 2251-2256.

Petermeier, H., Benning, R., Becker, T., Delgado, A., 2003. Numero-fuzzy hybrid for modelling and simulation of the fouling of milk heat exchangers. PAMM · Proc. Appl. Math. Mech. 3, 470-471.

Picón-Núñez, M., López Robles, J.L., 2005. Flow passage arrangement and surface selection in multi-stream plate-fin heat exchangers. Heat Transfer Engineering 26, 5-14.

Picon-Nunez, M., Polley, G.T., 2000. Methodology for the design of multi-stream plate-fin heat exchangers. in: Sunden, B., Heggs, P.J., (Eds.), Recent Advances in Analysis of Heat Transfer for Fin Type Surfaces. WIT Press, 251-276.

Picon-Nunez, M., Polley, G.T., Medina-Flores, M., 2002. Thermal design of multistream heat exchangers. Applied Thermal Engineering 22, 1643-1660.

Polley, G.T., Picon-Nunez, M., 2001. Understanding multi-stream heat exchanger design. February, Available from: <www.pinchtechnolgy.com>.

Ponce-Ortega, J.M., Serna-González, M., Jiménez-Gutiérrez, A., 2008. Synthesis of multipass heat exchanger networks using genetic algorithms. Computers and Chemical Engineering 32, 2320-2332.

Ponce-Ortega, J.M., Serna-González, M., Jiménez-Gutiérrez, A., 2009. Use of genetic algorithms for the optimal design of shell-and-tube heat exchangers. Applied Thermal Engineering 29, 203-209.

Prasad, B.S.V., 1991. The performance prediction of multi-stream plate fin heat exchangers based on stacking pattern. Heat Transfer Engineering 12, 58-70.

Prasad, B.S.V., 1996a. Fin efficiency and mechanisms of heat exchange through fins in multi-stream plate fin heat exchangers: formulation. International Journal of Heat and Mass Transfer 39, 419-428.

Prasad, B.S.V., 1996b. The sizing and passage arrangement of multi-stream plate-fin heat exchangers. Heat Transfer Engineering 17, 35-43.

Prasad, B.S.V., 1997. Fin efficiency and mechanisms of heat exchange through fins in multi-stream plate fin heat exchangers: development and application of a rating algorithm. International Journal of Heat and Mass Transfer 40, 4279-4288.

Prasad, B.S.V., Gurukul, S.M.K.A., 1987. Differential method for sizing multi-stream plate fin heat exchangers. Cryogenics 27, 257-262.

Prasad, B.S.V., Gurukul, S.M.K.A., 1992. Differential methods for the performance prediction of multi-stream plate fin heat exchangers. Journal of Heat Transfer 114, 41-49.

Pratihar, D.K., 2008. Soft Computing. Narosa Publishing House, New Delhi, India.

Prud'homme, M., Nguyen, T.H., 1999. Fourier analysis of conjugate gradient method applied to inverse heat conduction problems. International Journal of Heat and Mass Transfer 42, 4447-4460.

Prud'homme, M., Nguyen, T.H., 2001. Solution of the inverse steady state convection problem in a porous medium by adjoint equations. International Communications in Heat and Mass Transfer 28, 11-21.

Pulido-Calvo, I., Gutiérrez-Estrada, J.C., 2009. Improved irrigation water demand forecasting using a soft computing hybrid model. Biosystems Engineering 102, 202-218.

Ragland, W.A, France, D.M., Minkowycz, W.J., 1989a. Two-phase flow at the flooding point in an annulus. Experimental Thermal and Fluid Science 2, 7-16.

Ragland, W.A, Minkowycz, W.J., France, D.M., 1989b. Single-and double-wall flooding of two-phase flow in an annulus. Int. J. Heat and Fluid Flow 10, 103-109.

Rahim, R.A., Fea, P.J., San, C.K., Chean, L.L., 2005. Real-time image reconstruction for various flow regimes using an optical tomography sensor in a gravity flow conveyor. Advanced Powder Technol 16, 399-411.

Raudenský, M., Horský, J., Krejsa, J., 1995. Usage of neural network for coupled parameter and function specification inverse heat conduction problem. International Communications in Heat and Mass Transfer 22, 661-670.

Ravagnani, M.A.S.S., Silva, A.P., Arroyo, P.A., Constantino, A.A., 2005. Heat exchanger network synthesis and optimisation using genetic algorithm. Applied Thermal Engineering 25, 1003-1017.

Reinecke, N., Mewes, D., 1997. Multielectrode Capacitance sensors for the visualization of transient two-phase flows. Experimental Thermal and Fluid Science 15, 253-266.

Reneau, L.R., Johnston, J.P., Kline, S.J., 1967. Performance and design of straight, two-dimensional diffusers. Journal of Basic Engineering 89, 141-150.

Reuther, J., Jameson, A., Alonso, J., Rimlinger, M., Saunders, D., 1999a. Constrained multipoint aerodynamic shape optimization using an adjoint formulation and parallel computers, Part 1. Journal of Aircraft 36, 51-60.

Reuther, J., Jameson, A., Alonso, J., Rimlinger, M., Saunders, D., 1999b. Constrained multipoint aerodynamic shape optimization using an adjoint formulation and parallel computers, Part 2. Journal of Aircraft 36, 61-74.

Revankar, S.T., Chang, J.S., 1984a. Counter-current flooding phenomena in gas-liquid two-phase flow under an electric field-part1: Theoretical analysis for the adiabatic case in a vertical tube. Journal of Electrostatics 16, 47-68.

Revankar, S.T., Chang, J.S., 1984b. Counter-current flooding phenomena in gas-liquid two-phase flow under an electric field-part2: Theoretical analysis for the non-adiabatic case in a vertical tube. Journal of Electrostatics 16, 69-77.

Riganti, R., 1991. A solution technique for random and inverse heat conduction problems. Mathematics and Computers in Simulation 33, 51-64.

Riverol, C., Napolitano, V., 2002. Estimation of the overall heat transfer coefficient in a tubular heat exchanger under fouling using neural networks. Application in a flash pasteurizer. Int. Comm. Heat Mass Transfer 29, 453-457.

Rowe, W.B., Willmore, J.I., Hulton, L.J., 1973. A technique for simulation of cylindrical grinding process by hybrid computation. International Journal of Machine Tool Design and Research 13, 111-121.

Ruiz-Mercado, C., Pacheco-Vega, A., Peters, K., 2006. On-line fuzzy logic temperature control of a concentric-tubes heat exchanger facility. ASME Proc. International Mechanical Engineering Congress and Exposition, Chicago, Illinois, USA, pp. 767-773.

Santos, M., Dexter, A.L., 2002. Control of a cryogenic process using a fuzzy PID scheduler. Control Engineering Practice 10, 1147-1152.

Sarkar, D., Modak, J.M., 2003. ANNSA: a hybrid artificial neural network/simulated annealing algorithm for optimal control problems. Chemical Engineering Science 58, 3131-3142.

Sebakhy, E.A.E., 2010. Flow regimes identification and liquid-holdup prediction in horizontal multiphase flow based on neuro-fuzzy inference systems. Mathematics and Computers in Simulation 80, 1854-1866.

Sekoguchi, K., Inoue, K., Imasaka, T., 1987. Void signal analysis and gas–liquid two-phase flow regime determination by a statistical pattern recognition method. JSME Int. J. 30, 1266-1273.

Selbaş, R., Kızılkan, Ö., Reppich, M., 2006. A new design approach for shell-and-tube heat exchangers using genetic algorithms from economic point of view. Chemical Engineering and Processing 45, 268-275.

Sen, M., 2003. A review of principles and applications of thermal control. http://nd.edu/~msen/Teaching/IntSyst/Text5.pdf, 1-24.

Sen, M., Goodwine, B., 2002. Soft computing in control. The MEMS Handbook, M. Gad-el-Hak, ed., CRC, Boca Raton, FL, ch. 14, pp. 1-37.

Sen, M., Yang, K.T., 2000. Applications of artificial neural networks and genetic algorithms in thermal engineering. CRC Handbook of Thermal Engineering, F. Kreith, ed., CRC, Boca Raton, FL, pp. 4-620--4-661.

Sharma, H., Das, G., Samanta, A.N., 2006. ANN-Based prediction of two-phase gas-liquid flow patterns in a circular conduit. American Institute of Chemical Engineers 52, 3018-3028.

Shiguemori, E.H., da Silva, J.D.S. Campos Velho, H.F.D., 2004. Estimation of initial condition in heat conduction by neural network. Inverse Problems in Science and Engineering 12, 317-328.

Shiguemori, E.H., Harter, F.P., Campos Velho, H.F., da Silva, J.D.S., 2002. Estimation of boundary conditions in conduction heat transfer by neural networks. Tendências em Matemática Aplicada e Computacional 3, 189-195.

Sorlie, T., 1962. Three fluid heat exchanger design theory, counter and parallel flow. Technical Report 54, Department of Mechanical Engineering, Stanford University, Stanford.

Stephen, E.A., Shnathi, M., Rajalakshmy, P., Parthido M.M., 2010. Application of fuzzy logic in control of thermal comfort. International Journal of Computational and Applied Mathematics 5, 289-300.

Suessmann, W., Mansour, A., 1979. Passage arrangements in plate-fin heat exchanger, in: Proc. of 15th International Congress of refrigeration, Venice, 421-429.

Sunder, S., Fox, V.G., 1993. Multivariable Optimization of Plate Fin Heat exchangers. AIChE Symposium Series, Atlanta, 244-252.

Suzuki, S., Ueda, T., 1977. Behaviour of liquid films and flooding in counter-current two-phase flow-part 1. Flow in circular tubes. Int. J. Multiphase Flow 3, 517-532.

Suzuki, Y., Nakagawa, M., Aritomi, M., Murakawa, H., Kikura, H., Mori, M., 2002. Microstructure of the flow field around a bubble in counter-current bubbly flow. Experimental Thermal and Fluid Science 26, 221-227.

Svenningsen, K.H., Madsen, J.I., Päuker, W.H.G., Hassing, N.H., 1996. Optimization of flow geometries applying quasi-analytical sensitivity analysis. Applied Mathematical Modelling 20, 214-224.

Swanson, G.D., Carpenter Jr., T.M., Snider, D.E., Bellville, J.W., 1971. An on-line hybrid computing system for dynamic respiratory response studies. Computer and Biomedical Research 4, 205-215.

Taitel, Y., Barnea, D., 1983. Counter current gas-liquid vertical flow, model for flow pattern and pressure drop. Int. J. Multiphase Flow 9, 637-647.

Taler, J., Duda, P., Węglowski, B., Zima, W., Grądziel, S., Sobota, T., Taler, D., 2009. Identification of local heat flux to membrane water-walls in steam boilers. Fuel 88, 305-311.

Telejko, T., Malinowski, Z., 2004. Application of an inverse solution to the thermal conductivity identification using the finite element method. Journal of Materials Processing Technology 146, 145-155.

Teyssedou, A., Önder, E.N., Tye, P., 2005. Air-water counter-current slug flow data in vertical-to-horizontal pipes containing orifice type obstructions. Int. J. Multiphase Flow 31, 771-792.

Tien, C.L., 1977. A simple analytical model for counter-current flow limiting phenomena with vapor condensation. Letters in Heat and Mass Transfer 4, 231-238.

Tracy, F.T., 2008. One-, two-, and three-dimensional solutions for counter-current steady-state two-phase subsurface flow. Int. J. Multiphase Flow 34, 437-446.

Trifonov, Y.Y., 2010. Flooding in two-phase counter-current flows: Numerical investigation of the gas-liquid wavy interface using the Navier-Stokes equations. Int. J. Multiphase Flow 36, 549-557.

Tso, C.P., Chan, S.W., Chan, S.F., 1988. Air-water counter-current flow limits in a vertical pipe filled with spheres. Experimental Thermal and Fluid Science 1, 207-219.

Tsoukalas, L.H., Ishii, M., Mi, Y., 1997. A Neuro-fuzzy methodology for impedance-based multi-phase flow identification. Engng Applic. Artif. Intell 10, 545-555.

Tutmez, B., 2009. Use of hybrid intelligent computing in mineral resources evaluation. Applied Soft Computing 9, 1023-1028.

Ueda, T., Suzuki, S., 1978. Behaviour of liquid films and flooding in counter-current two-phase flow-part 2. Flow in annuli and rod bundles. Int. J. Multiphase Flow 4, 157-170.

Varshney, K., Panigrahi, P.K., 2005. Artificial neural network control of a heat exchanger in a closed flow air circuit. Applied Soft Computing 5, 441-465.

Volle, F., Maillet, D., Gradeck, M., Kouachi, A., Lebouché, M., 2009. Practical application of inverse heat conduction for wall condition estimation on a rotating cylinder. International Journal of Heat and Mass Transfer 52, 210-221.

Wang, H., Kondo, S., 1990. A study on the stratified horizontal counter-current two-phase flow. Nuclear Engineering and Design 121, 45-52.

Wang, L., Li, L., 2010. An effective hybrid quantum-inspired evolutionary algorithm for parameter estimation of chaotic systems. Expert Systems with Applications 37, 1279-1285.

Wang, L., Sunden, B., 2001. Design methodology for multi-stream plate fin heat exchangers in heat exchangers networks. Heat Transfer Engineering 22, 3-11.

Wang, S., Shoji, M., 2002. Fluctuation characteristics of two-phase flow splitting at a vertical impacting T-junction. International Journal of Multiphase Flow 28, 2007-2016.

Weber, C.F., 1981. Analysis and solution of the ill-posed inverse heat conduction problem. International Journal of Heat and Mass Transfer 24, 1783-1792.

Wei, G.-F., Yao, P.-J., Qian, Y., 2006. Development of optimization algorithm for synthesizing multi-stream heat exchanger network. Huanan Ligong Daxue Xuebao Journal of South China University of Technolog 34, 6-12.

Wei-zhong, A., Fengjuan, Y., Fenglei, D., Yangdong, H., 2008. Simulated Annealing Approach to the Optimal Synthesis of Distillation Column with Intermediate Heat Exchangers. Chinese Journal of Chemical Engineering 16, 30-35.

Wei-zhong, A., Xi-Gang, Y., 2009. A simulated annealing-based approach to the optimal synthesis of heat-integrated distillation sequences. Computers and Chemical Engineering 33, 199-212.

Whittaker, G., Confesor, R. Jr, Griffith, S.M., Färe, R., Grosskopf, S., Steiner, J.J., Mueller-Warrant, G.W., Banowetz, G.M., 2009. A hybrid genetic algorithm for multiobjective problems with activity analysis-based local search. European Journal of Operational Research 193, 195-203.

Wintterle, T., Laurien, E., Stäbler, T., Meyer, L., Schulenberg, T., 2008. Experimental and numerical investigation of counter-current stratified flows in horizontal channels. Nuclear Engineering and Design 238, 627-636.

Wolf, J., 1964. General solution of the equations of parallel flow multi-channel heat exchangers. International Journal of Heat and Mass Transfer 7, 901-919.

Wu, Z., Ding, G., Wang, K., Fukaya, M., 2008. Application of a genetic algorithm to optimize the refrigerant circuit of fin-and-tube heat exchangers for maximum heat transfer or shortest tube. International Journal of Thermal Sciences 47, 985-997.

Xie, D., Luo, Z., Yu, F., 2009. The computing of the optimal power consumption for semi-track air-cushion vehicle using hybrid generalized extremal optimization. Applied Mathematical Modelling 33, 2831-2844.

Xie, G.N., Sunden, B., Wang, Q.W., 2008. Optimization of compact heat exchangers by a genetic algorithm. Applied Thermal Engineering 28, 865-906.

Xie, G.N., Wang, Q.W., Zeng, M., Luo, L.Q., 2007. Heat transfer analysis for shell-and-tube heat exchangers with experimental data by artificial neural networks approach. Applied Thermal Engineering 27, 1096-1104.

Xie, T., Ghiaasiaan, S.M., Karrila, S., 2004. Artifi-cial neural network approach for flow regime classifi-cation in gas-liquid-fiber flows based on frequency domain analysis of pressure signals. Chemical Engineering Science 59, 2241-2251.

Xu, L., Han, Y., Xu, L.A., Yang, J., 1997. Application of ultrasonic tomography to monitoring gas/liquid flow. Chemical Engineering Science 52, 2171-2183.

Xu, L.J., Xu, L.A., 1997. Gas/liquid two-phase flow regime identification by ultrasonic tomography. Flow Measurement and Instrumentation 8, 145-155.

Yang, C.Y., 1998. Solving the two-dimensional inverse heat source problem through the linear least-square error method. International Journal of Heat and Mass Transfer 41, 393-398.

Yang, C.Y., 1999. Estimation of the temperature-dependent thermal conductivity in inverse heat conduction problems. Applied Mathematical Modelling 23, 469-478.

Yang, K.T., 2007. Role of Artificial Intelligence (AI) in Thermal Sciences and Engineering," ASME Paper No. HT-2007-32042.

Yang, K.T., 2008. Artificial Neural Networks (ANNs): A new paradigm for thermal science and engineering. Journal of Heat Transfer 130, 093001-1-- 093001-19.

Yoo, T., Cho, H., Yücesan, E., 2010. Hybrid algorithm for discrete event simulation based supply chain optimization. Expert Systems with Applications 37, 2354-2361.

Yuan, Z.X., Ma, Y.L., Xia, G.P., Tao, W.Q., 1997. Computer implementation of the passage arrangement for plate-fin heat exchangers according to local balance principle. Journal of Thermal Science 6, 190-196.

Zadeh, L.A., 1976. Foreword. Proc. Second International Conference on Fuzzy Logic and Nural Networks, Iizuka, Japan, pp. XIII-XIV.

Zaleski, T., 1984. A general mathematical model of parallel flow-multi-channel heat exchangers and analysis of its properties. Chemical Engineering Science 39, 1251-1260.

Zhang, L., Wang, H., 2010a. Identification of oil-gas two-phase flow pattern based on SVM and electrical capacitance tomography technique. Flow Measurement and Instrumentation 21, 20-24.

Zhang, W.H., Li, H., Li, X., 2010b. Identification of regime transitions in an inner-loop airlift reactor using local bubble-induced pressure fluctuation signals. Chemical Engineering Journal 162, 296-300.