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A robust predictive technique for the pressure drop during condensation in inclined smooth tubes

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ABSTRACT

The pressure drop during condensation in inclined tubes at different saturation temperatures is one of the most important design parameters in many applications. Due to need of huge investments for providing a highly equipped laboratory and difficulties in data collection over challenging situations, developing a high performance predictive model is helpful to design and optimize condensers with lower pumping costs as a result of accurate estimation of pressure drops. In this communication, the potential of four different universal intelligent models, particle swam optimization-artificial neural network (PSO-ANN), genetic algorithm-least square support vector machine (GA-LSSVM), hybrid approach-adaptive neuro fuzzy inference system (Hybrid-ANFIS), and genetic algorithm-power law committee with intelligent systems (GA-PLCIS) are evaluated for precise estimating the pressure drop (ΔP) and frictional pressure drop (ΔP_{fric}). The comparative results demonstrated that the developed GA-LSSVM, Hybrid-ANFIS, and GA-PLCIS models could be implemented to establish favorable predictions for the application of interest. Nevertheless, the GA-PLCIS models by combining the merits of the single developed models indicate higher performance by introducing a $R^2 = 0.9990752581$, MSE = 0.0140, and RRMSE = 2.4983 for the ΔP and a $R^2 = 0.9990960793$, MSE = 0.0126, and RRMSE = 2.2414 for the ΔP_{fric}. Based on the results, the GA-PLCIS can be taken into account as a practical and easy-to-use model with high accuracy predicting performance, which is highly helpful for engineers to monitor the precise results under different conditions, even in the challenging situations such as low mass fluxes and low qualities.

1. Introduction

Heat exchangers have a wide variety of application in almost all branch of engineering to transfer heat between different fluids, which have different temperatures. Some of the examples of using heat exchangers are in the refrigeration and heat pump systems, power production facilities, and chemical processes. Therefore, from a practical application point of view, it is logically acceptable that deep knowledge about such components and their effecting parameters are of importance to design such components for a better overall performance.

The pressure drop during condensation, where two-phase flow exists, plays a highly important role in heat exchangers or condensers, since impacts the pumping costs and subsequently the heat transfer and overall system performance. To enable the development of condensers, several experimental and numerical research works have been conducted on two-phase pressure drop in horizontal [1–5] and vertical [6–8] orientations to study and predict its nonlinear trend, as two-phase flow in tubes is the most challenging phenomenon in condensers [9].

In recent years, condensation in inclined tubes has found an attention due to its wide applications including aeroplanes during takeoff, landing and banking, automobiles and trucks driving over hilly terrains, and large industrial A- and V-frame condensers [10]. Despite being an important topic, a few scholars have studied the pressure drop in the type of tubes. The effect of inclination on the pressure drops was experimentally studied by Lips and Meyer [11] under constant saturation temperature, i.e., 40 °C. In this study, the results were compared against different correlations in the open literature for the horizontal and vertical orientations. Recently, Adelaja et al. [10] experimentally investigated the pressure drop during condensation in an inclined smooth copper tube at saturation temperatures of 30 °C, 40 °C and 50 °C in order to elucidate influence of different parameters considering the refrigerant R134a. As a result, the impacts of inclination angle and saturation temperature on pressure drop were dictated.

Nevertheless, to characterize the pressure drop during condensation in inclined smooth tubes at different saturation temperatures, sufficient and nettlesome experiments should be conducted. Additionally, such approaches are difficult, tedious, and time wasting, which need a lot of investments to provide a highly equipped laboratory and proper

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instruments. On the other hand, there are some challenging situations such as low mass fluxes and low qualities where collecting data is difficult. Actually, two-phase flow consists of all the complexities of single-phase flows as well as two-phase characteristics [12]; thus, development of the numerical approaches and computer technologies make it possible to tackle complex and ill-defined problems, even the pressure drop during condensation in inclined tubes where there are complex inter-relations among the influential parameters.

Quiben and Thome [12] summarized the available models in the open literature for predicting the pressure drops into three categories, namely empirical correlations, analytical models, and phenomenological models. The limitations and drawbacks of the existing modeling approaches are discussed in detail in the addressed paper. Further to the above, the difficulty of estimating the pressure drops due to dependence on the flow patterns was mentioned by Lips and Meyer [13]. As noted before, due to the complexity of the problem of concern and the large deviations from the actual data using the existing models for two-phase pressure drop during condensation, developing a robust, practical, and easy-to-use computer simulation program is highly desirable.

In the past two decades, artificial neural algorithms have been widely used for solving nonlinear and complex problems in different branch of engineering. The advantages of such approaches, in comparison with the conventional ones, are that they can model complex and nettlesome problems with high precision while decreasing computational time. This claim has been proven by a variety of research studies published by experts in different research areas, such as nanorefrigerant [14], solar [15], chemical [16], heating, ventilation and air conditioning [17], and heat transfer [18]. Balcilar et al. [19] developed four different artificial neural networks in order to predict the heat transfer coefficient and the pressure drop of R134a flowing downward inside a vertical smooth copper tube. Finally, the authors concluded that the new developed models outperformed the empirical models and the correlations proposed in the authors' previous publications. In another study, Balcilar et al. [20] investigated the application of artificial neural network for estimating the pressure drop of different refrigerants during condensation and evaporation in horizontal smooth and micro-fin tubes. A satisfactory result in comparison with experimental data that were gathered from open literature was reported. Recently, Mohanraj et al. [21] specifically focused on the applications of artificial neural networks for thermal analysis of heat exchangers and a comprehensive review was conducted.

To sum up, previous research studies confirmed the possibility of applying artificial intelligence methods for solving complex problems in different research areas. Recently, Azizi and Ahmadloo [22] used previously published data and developed an artificial neural network to predict the heat transfer coefficient during condensation of R134a in inclined smooth tubes. However, to the best of our knowledge, there is still a lack of effective attempts to use artificial intelligence methods to predict the pressure drop (ΔP) and frictional pressure drop (ΔP_{fric}) during condensation in inclined tubes at different saturation temperatures, which is currently in great need of a precise and fast predictive model for researchers and designers. Therefore, this communication indicates a strong motivation to introduce a novel predictive model using soft computing approaches. The appropriate input variables are selected and predictabilities of the constructed techniques are assessed by conducting a comparative study between the predicted values and the corresponding actual data in order to evaluate their effectiveness by mans of various statistical and graphical error tests.

2. Data set

In order to develop a reliable approach for estimating the pressure drop and frictional pressure drop, the previously published experimental data in the literature were collected. Two data banks with 337 and 312 data samples were extracted from the report of Adelaja et al. [10] for respective the pressure drop and frictional pressure drop. Each data consists of four inputs: the inclination angle, the mass flux, the vapor quality, and the saturation temperature. The ranges of the used parameters are summarized in Table 1. In advance of the simulation, the inputs and outputs were normalized between 0.1 and 0.9 in order to make the computational easier and increase the learning speed.

Table 1
The statistics of the input data samples.

Parameters	Unit	Min	Max	Average
Inclination angle	°	− 90	90	0
Mass flux	Kg/m^3 s	100	400	250
Vapor quality	%	10	90	50
Saturation temperature	°C	30	50	40

The gathered data have been split in a random manner to determine the predictabilities of the models. To this end, 75% and 25% of the data sets were allocated for the training and testing phases, respectively. For the sake of a fair comparative study, the same training and testing sets are considered when developing all the predicting models.

3. Proposed methodology

3.1. Optimization techniques

3.1.1. Genetic algorithm (GA)

GA was designed by means of the concept of Darwinian theory to achieve the optimal solution using evolutionary rules. GA starts considering a set of potential solutions, known also as individuals, instead of the single points. The nature of a problem is the parameter that influences the number of the individuals. The individuals are modified using different operators. To create a new generations or children, GA chooses those individuals in the population that are closer to the global optimum in order to share their genes. Inherently, GA consists of four operators called population, crossover, mutation, and reproduction. The algorithm working process is stopped if a stopping condition such as maximum number of iterations or desired fitness function range is met. Otherwise, the four stages repeatedly modify individuals and the procedure is continued till reaches to an acceptable answer [23].

3.1.2. Particle swam optimization (PSO)

Inspired by the concept of swarming or flocking animals, PSO is a novel optimizer that is used for optimizing different problems. The simplicity as well as a few adjustable parameters over the other techniques make PSO as a popular optimization technique to be utilized for solving different problems. In this algorithm, firstly, the swarm of the particles in a random manner along with speeds and locations are initialized. Afterwards, fitness value of each particle is calculated and compared via a statistical function by defining fitness function, which finally results to determine the position of the best particle. In general, the locations and speeds of all particles are revised until convergence or a stopping condition is fulfilled [24].

3.2. Intelligent models

3.2.1. Multilayer perceptron-artificial neural network (MLP-ANN)

ANNs are the conventional types of neural networks, which are basically similar to the biological nervous system. These models can be counted as an interesting alternative way for the numerical approaches, which are able to tackle ill-defined and nonlinear problems. The MLP-ANN architecture is the most common type of ANNs [25]. This particular network comprises three layers: an input layer, one or more hidden layers, and an output layer. Each layer consists several nodes, which are called neuron. The neurons are connected to each other in a parallel structure. The information from the regression problem is