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Artificial neural networks applied to heat exchangers problems: a review

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Abstract. Artificial Neural Networks (ANN) are computational algorithms inspired by the nervous system of animals. They are powerful tools to predict patterns and behaviors for problems in different fields of study. Heat exchangers are devices created to improve heat transfer that are hard to model by conventional methods but are highly important in many applications. ANN have been used to model heat exchange problems, thus, helping to predict and analyze patterns and behaviors not easily predicted by traditional methods. This review discusses the application of ANN to heat exchanger problems, evaluating the improvement in the field over the last decades. To achieve this goal, the number of publications was first analyzed, and the studies were divided into groups according to the research goals. It was also analyzed the number of publications each year. It was considered the keywords: "artificial neural network" and "heat exchanger" in the Science Direct platform. One hundred nine papers were found, and around 50% were published in the last five years. 68% of the articles focused on the evaluation of the ANN rather than utilizing it to optimize heat exchangers, showing that the method is still in development even if it has become more important in the last decade.

Keywords: Artificial Neural Networks; Heat Exchanger; Comprehensive Review

1 Introduction

Artificial neural networks (ANN) are, as said by Haykin [1], essentially computer algorithms made to model the way a brain or a nervous system performs a task. In recent years, numerous researches have been done on the optimization and use of ANN to solve pattern recognition problems in many fields. These approaches are typically proposed for problems with complex modeling using conventional methods since the use of artificial neural networks method can be made without the usually needed equations in complex problems. In numerous cases, using ANN offers better performance, high adaptability, tolerance to unexpected patterns, easy implementation, and other characteristics required [2].

One field in which ANN have been rapidly developing is heat exchange problems. Heat exchangers are devices used to improve the heat transfer between two surfaces. These devices are widely used in industry sectors such as power plants, oil and gas, and heat recovery. They are also used in simpler processes such as air conditioning in houses and stores [3, 4]).

Equipment used to promote heat exchange are essential for the system they are used. Usually, the heat exchanger can be the limiter of the system efficiency, and an improvement in the heat exchange means that the heat needed for a process is reduced or the losses are reduced, and with it, the energy loss of the system and process. That could mean profit increases or less environmental impact, both significant nowadays.

Many heat exchangers work through convective processes, that are in general complex and hard to model, typically needing to estimate the properties of the fluid and make many approximations to achieve a viable result that still has significant variations in accuracy [5].

The use of ANN for pattern recognition of heat exchangers is increasing mainly because of the characteristics of the neural network in finding results in problems that the theory is not known about. Since the quality of the result depends only on how well the data used is representative of the system's behavior, many complex systems can be modeled with ANN within less time and effort than analytic methods and with more precision, limited only by the data acquisition needed.

The main objective of this systematic literature review is to summarize the works on the use of artificial neural networks to model heat exchange devices, identifying and summarizing the principal characteristics of the ANN utilized and the improvement of the method through the last years.

2 Literature review

This section introduces the theory of artificial neural networks and heat exchangers and the utilization of ANN in the subject.

2.1 Artificial Neural Networks

ANN consist of a group of computational algorithms made to solve problems based on how the nervous system of superior organisms works. The method uses computed data to "teach" the neural network the patterns it should model. Using these computational tools, it is possible to find a candidate solution to complex problems using repetitive simple computational operations. The problems to be solved using ANN could be non-analytical, nonlinear, nonstationary, nonstochastic, and even need to be solved for many variables. And even then, the algorithms still can have a good solution provided that the artificial neural network is well prepared and the database is reliable [6].

The use of ANN in the last decade grew with the rapid increase in the processing power, allowing the highly demanding process of training some algorithms to become viable. Using this newly available approach, it was observed a big growth in the research using computational algorithms, that are no longer limited to easy problems, to evaluate and validate a diversity of new subjects.

The structure of an artificial neural network can vary greatly depending on the model used. Still, some characteristics are common: An ANN is composed of processing units typically called neurons in analogy to the biological system in which they are inspired. Each neuron receives an input processed by a determined function inside the neuron and then generates an output. The output shown by an ANN is the result of inserting data in the first layer of neurons. This information is processed and transmitted between the neurons inside the system until it reaches the output layer of neurons, where it could be read [1, 7].

2.2 Heat exchangers

It is common, in many sectors of the industry, the necessity to have precise control of the process temperature. In this way, heat exchangers are the thermodynamic devices responsible for maintaining this temperature. The efficiency of the exchanger is one of the factors that will result in a process with precise temperature and low energy loss, which is essential to produce a high-quality product with the lowest price and environmental impact [3, 8].

The most common ways to classify the heat exchangers are by their structure and fluid flux. One of the most used classes of heat exchangers is the shell and tube. As the name implies, it is composed of a vessel, normally high pressured, with small tubes inside it. The heat exchange occurs when one fluid passes through the small pipes and inside the vessel that is filled with fluid at another temperature.

Another well-known heat exchanger model is the Double-pipe. In this case, the device is composed of two cylinders of different diameters, one inside the other. One of the fluids flows through the internal pipe, and the other runs through the gap between tubes transferring heat from one to another.

Commonly, and in both cases of heat exchanger described, the fluids flow could be counter flow, where the fluids enter through different extremities and flow in opposing directions, and parallel flow when the fluids enter the system in the same extremity and run in the same direction [3, 8].

Heat exchangers usually use a fluid that transfers heat by convection between two surfaces that transfer heat by conduction. The conduction is a relatively simple process that can be predicted with an acceptable precision using empiric methods. Because of this, convection is normally the most challenging part of modeling the system since it depends on the fluid propriety and the flux passing through the exchanger, both complex properties to predict with precision.

2.3 Evaluation of ANN applied to heat exchangers

As the use of artificial neural networks for modeling heat exchange problems is a promising area that has yet to become a widely widespread technology, most of its research still focuses on evaluating the applicability of the various ANN algorithms in several systems with heat exchangers.

Moya-Rico et al. [9] used a multi-layer perceptron (MLP) artificial neural network to predict the heat transfer and the pressure drop in a triple concentric-tube heat exchanger. The experiment examined various combinations of the number of neurons, hidden layers, and different training algorithms (Levenberg-Marquardt, Bayesian Regulation, and Scaled conjugated gradient), comparing their accuracy and computational time. The results show good agreement between the experimental value and the results found with the ANN confirmed by the low absolute relative deviation (AARD%) found, of 2% for heat transfer and 4% for pressure drop, concluding that the ANN models are a helpful tool to predict the performance of the heat exchanger evaluated.

The use of an ANN as a new approach to predict the heat transfer coefficient of a thermoacoustic heat exchanger was evaluated by Rahman and Zhang [10]. The study uses Multilayer Perceptron (MLP)The neural network is structured with one hidden layer, and the number of neurons in this layer varied from 2 to 20, checking for the best result. The inputs are the mean pressure and the frequency, and the output is the heat transfer coefficient. The authors conclude that the MLP has high accuracy with an average percentual error of 3.2%, showing that the ANN can be used to provide fast and consistent results.

2.4 Evaluation of a heat exchanger using ANN

The ANN can be used when the objective is to optimize and evaluate the results shown for a heat exchanger. Using the obtained data, it is possible to predict the device's behavior in an environment that cannot be emulated and evaluate the obtained results using the ANN.

In their article, Mohammadi et al. [11] used MLP to predict the behavior of a shell and tube heat exchange with six porous baffles in unknown input values. The objective of the study was to test the proposed system experimentally. The experimental data were used for training the ANN with the Levenberg-Marquardt algorithm, and the results were used together with the experimental data to show the system's behavior even with inputs that could not be tested experimentally.

Gang et al. [12] studied the use of an ANN to optimize the control of a ground source heat pump. The proposed control strategy compares the temperature of the cooling water exiting the ground heat exchanger and the cooling tower. The comparison was made by calculating four years of the system based on the new approach with two other methods. The results show that the proposed system is more energy-efficient.

3 Method

A survey was conducted on the Science Direct platform, searching for research articles containing the keywords “artificial neural network” and “heat exchanger”. The studies were filtered, and the ones that consider applications of artificial neural networks in heat exchange systems were selected, the remaining researches were then categorized into two groups:

I - Evaluation of the ANN: To be placed in group I, the paper should be a study proposing an artificial neural network approach to a determined heat exchange system. The researches in this group evaluate the results of the utilization of the ANN, showing if the method show agreement with the experimental results or mathematical model.

II – Optimization and evaluation of the Heat exchanger using ANN: Group II gathers research that uses a proposed artificial neural network system to optimize heat exchange devices. The optimization is done by predicting patterns, results, geometries, and other characteristics that could be used to improve the functioning of the system.

The surveys were analyzed by its year of publication evaluating the development of the ANN applications in optimizing heat exchangers. The number of publications in each year, the number of research growth through the last decades, and the kind of studies that were performed were evaluated.

The found researches were then grouped by the ANN model utilized, evaluating the clarity in the utilization of the method and the most used algorithms.

4 Results and discussion

From the initial search, a total of one hundred fifty-eight articles were found, and each was examined and filtered, removing the ones that were not about the ANN application in heat exchange problems. One hundred nine articles were selected for the review.

In the remaining works, the year of publication was evaluated. The goal was to see the evolution of ANN use from the first found publication until nowadays. The result can be seen in Fig. 1.

It is possible to see how the number of research grew in the last two decades and more yet in the last five years that together have almost fifty percent of the total. That shows the interest in the ANN is growing. As the use of the method is relatively new, this growth is expected as new applications are found, and old ones give positive results. It is also expected that research uses with positive results bring new investments in the subject. The increase in publications can too be associated with the growth in the computer power seen in the last years since the capacity of the computer is a big limiter for ANN, given that their algorithms are typically iterative and depend on an enormous amount of small repetitive computations.

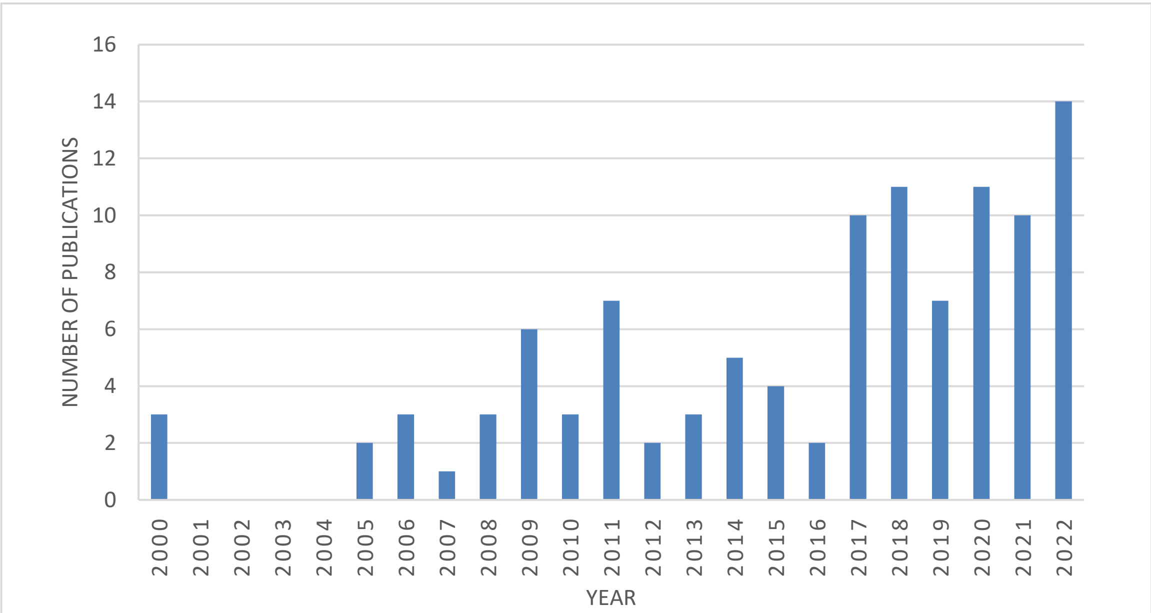

Figure 1. Number of publications each year

After the initial analyses, the papers were grouped into two categories, as seen in section 3. Each article was individually evaluated and placed in the group that better fits the search results, as shown in Tab. 1.

Table 1. Articles found split into two groups

Group	Article's objective	Number of articles found
I	Evaluation of ANN use in the heat exchanger	73
II	Optimization of the heat exchanger using ANN	34

It is shown in Fig. 2 (2000 - 2022) that from all the selected publications, about 68% are in group II, showing articles evaluating and studying the applicability of artificial neural networks, and these are the most common kinds of research. This information indicates that the technology is still in development, and it is expected that more papers trying to test and evaluate its efficiency and applicability are made. If compared, the number of studies using it to improve the heat exchanger will be smaller since the method is implicitly necessary to work in these cases.

Still evaluating Fig. 2 but now considering the results for two different periods (2000-2011 and 2012-2022). In the first period covering the years from 2000 to 2011, the fraction of research focused on the application of ANN was smaller, showing a percentage of fourteen percent of the total of publications. In comparison, the results for the other half of the total period, which starts in 2012 to 2022, have a lot less research focused only on the study of the artificial neural network. In these years, about thirty-nine percent of the total studies were in group II, almost three times the previous percentage.

The results show a tendency of the ANN to become more of a methodology for optimization and modeling than a theoretical approach, as it is still today in most cases. This, combined with the increase in the total research, makes artificial neural networks a promising method that starts to create space in the heat exchange field.

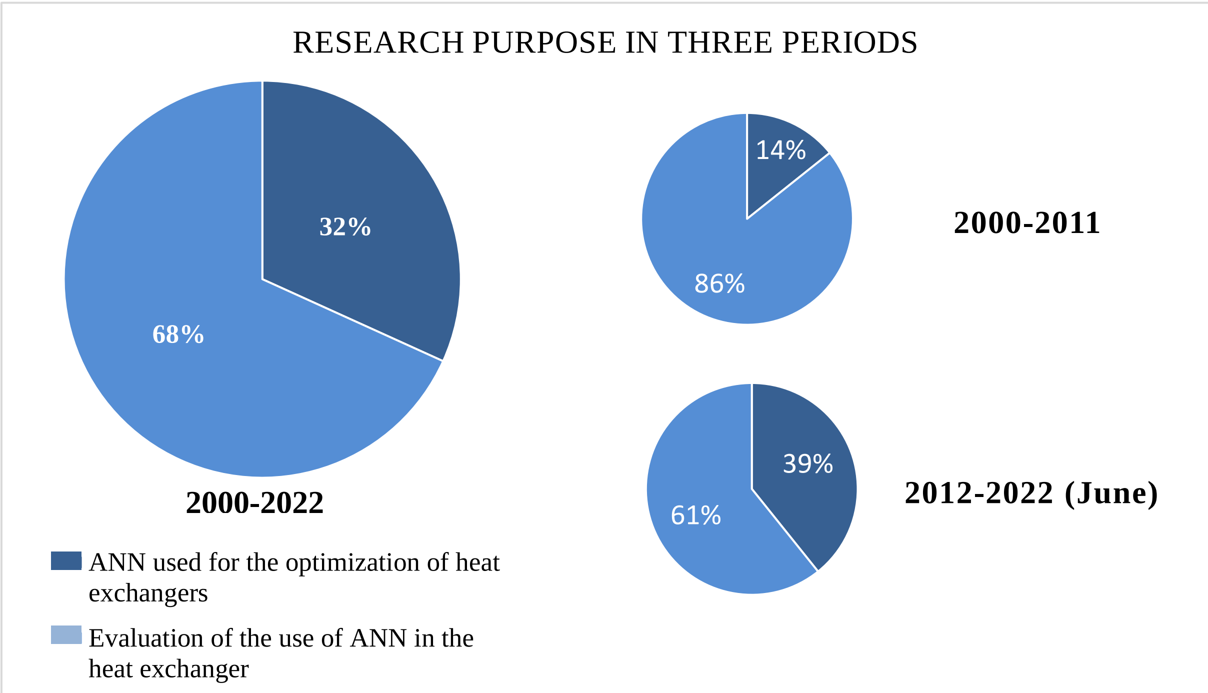

Figure 2. Proportion of papers in the two proposed groups for three different periods.

The papers were then grouped by the models of ANN used, and the results can be seen in Fig. 3. There is many different ANN that could be used in different problems bringing different results, but the multi-layer perceptron (MLP) is still the most common model used, primarily because of its easy implementation and good results with an extensive application range. The radial basis function (RBF) is a well-known ANN model and was the second most used in the papers evaluated. Even then, its use is far smaller compared to the MLP and it is normally used for comparison with other models.

A big problem experienced in this research was the low clarity of the characteristics of the ANN used, with 28% of the articles not specifying the model used. This creates a problem in references for new projects since it is difficult to replicate the application of the ANN. With this, there is a limitation to the reliability of the results shown and the model's applicability.

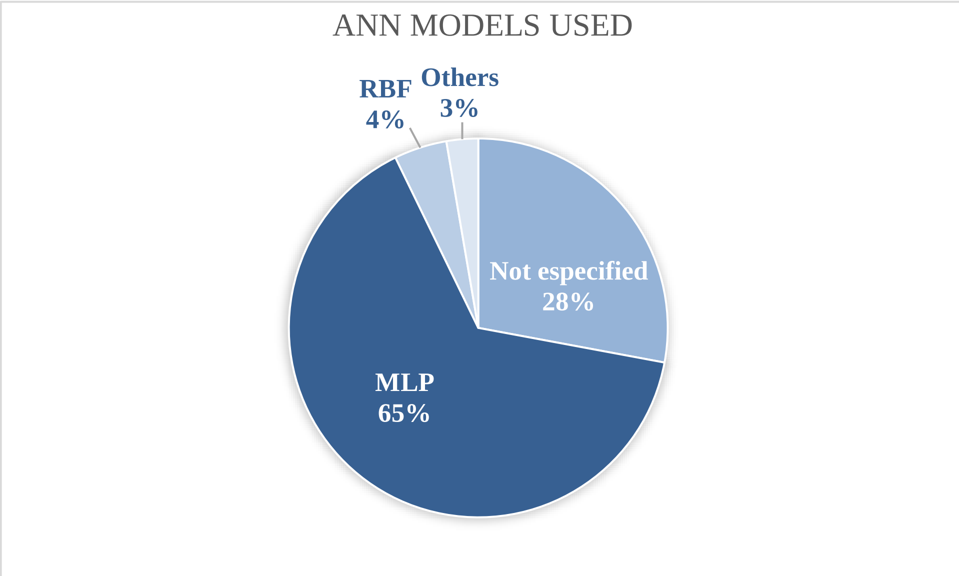

Figure 3. Evaluation of ANN models used in the papers found

5 Conclusions

This research evaluated the development of the use of artificial neural networks to model heat exchanger problems over the last two decades. Although the number of research is still small, it has grown in the last years and shows the potential to become a powerful tool to optimize and develop heat exchange-based systems.

The works found were, in the initial years, most initial studies evaluating the possibility of the application of ANN to model some simple problems. The studies made in this period focused on proving that the method could be used for a diversity of problems. In the last five years, there was a considerable increase in the number of publications, with half of the found surveys carried out in this period corroborating the growth trend of this technology that could be associated with the growth in processing power and with the popularization of computational methods.

It is shown, too, that the newest research has a significant fraction of applications of ANN that were utilized to optimize heat exchangers compared with studies focused on optimizing the artificial neural network. That shows a rise in the confidence of the method that is now not just a study material but a method with maturity to be used as a reliable and assertive method to recognize patterns.

It is possible to see that the use of ANN is still shallow and is restricted to the most common models, mostly MLP. This information shows that the perspective of growth is not just from the increase in the number of research but from the deepening in the various algorithms proposed that could be used in different systems with valuable results.

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