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Prediction of oscillatory heat transfer coefficient for a thermoacoustic heat exchanger through artificial neural network technique

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ABSTRACT

Heat exchangers under oscillatory flow condition in thermoacoustic devices are quite different with the traditional ones in heat transfer and flow behavior of thermo-viscous fluid. As a result, one cannot directly apply the heat transfer correlations for the steady flow to design thermoacoustic heat exchangers, otherwise, significant deviation will arise. However, some correlations of heat transfer for the oscillatory flow have not been well established yet. This study involves the application of artificial neural network (ANN) as a new approach to predict oscillatory heat transfer coefficient of one thermoacoustic heat exchanger under some operating conditions. One ANN model for the oscillatory heat exchanger used in one standing wave thermoacoustic refrigerator has been developed based on the published experimental data. This proposed ANN model has three layers with the configuration of 2-10-1, namely one input layer with two neurons representing two operating parameters, oscillating frequency and mean pressure, one hidden layer with optimal ten hidden neurons and one output layer with one neuron representing the oscillatory heat transfer coefficient as response. Moreover, a statistical analysis has been provided for studying the influence strength of these two input parameters on the oscillatory heat transfer coefficient. This ANN model had been proven to be desirable in accuracy for predicting oscillatory heat transfer coefficient by comparing ANN model results with both experimental results and calculated results by several other correlations from the published literature at the same operating conditions. This research work provides a new and accurate modeling approach based on ANN technique for the research of thermoacoustic heat exchangers and solving heat transfer problems related with oscillatory flow condition.

1. Introduction

Thermoacoustic technology deals with the conversion between thermal energy and acoustic energy (a kind of mechanical work) utilizing thermoacoustic effect, underlying which thermoacoustic devices can be developed to generate electricity or pump heat [1,2], with special advantages including using environmentally-friendly working substance such as air or inert gases, fewer or no moving parts and low maintenance, as well as being capable of using low grade thermal energy which will provide new opportunities for energy conservation [3]. Oscillating flow is a typical operating condition and physical feature encountered in thermacoustic devices where the gas parcels or liquids follow a periodic oscillatory motion, and a heat exchanger under oscillatory flow has been considered as one of the crucial components affecting the whole performance of thermoacoustic devices besides the thermoacoustic stack or regenerator. With the advancement of research and development of thermoacoustic technology, the heat transfer in oscillatory heat exchangers at two ends of stack/regenerator has been found to become a bottle neck to transfer the thermoacoustic heat flow in thermoacoustic devices. However, the fundamental theory and some practical correlations for the oscillatory heat transfer have not been well established yet. Therefore, the modeling, theoretical and experimental research concerning oscillatory flow and heat transfer is a necessary and urgent task for some applications under oscillatory flow environment, such as thermoacoustic engines or refrigerators, as well as the heat transfer enhancements using oscillating flow.

Typical design procedures for traditional compact heat exchangers generally refer to the heat transfer theory for a steady and unidirectional flow of fluid while thermoacoustic heat exchangers need to be designed based on oscillatory flow condition usually with zero mean velocity. The heat transfer characteristics under an oscillatory flow would be significantly different from those for unidirectional steady flow, due to the following facts that oscillating flow has two thermal entrance regions which make it enhance heat transfer [4]; Another hypothesis for the oscillatory

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flow is that the entrance length in a laminar reciprocating flow would be shorter than that in unidirectional steady flow; Additionally, the velocity profiles in an oscillatory flow, which nearly do not change in the entrance region, tend to be flatter than those of a steady flow [5]. These phenomena have not been fully understood yet due to the scarcity of experimental data and some complexities in mathematical modeling [4]. Because of these differences above, conventional heat transfer correlations for the steady flow cannot be directly applied to estimate the heat transfer coefficient between gas and solid walls for thermoacoustic heat exchangers, otherwise significant deviation in accuracy will arise [6]. In the present study, one artificial neural network (ANN) as a new approach was applied to predict oscillatory heat transfer coefficient for one thermoacoustic heat exchanger. Oscillating frequency and mean pressure are considered as two important factors influencing oscillatory heat transfer which will be investigated in this paper.

One ANN model is considered a purely data driven model, and it learns from examples where inputs and outputs are introduced to the network sequentially and repeatedly. The computation in ANN model is distributed over simple several units called neurons which are interconnected and operated in parallel. Hence, it is a simple, rapid and accurate model. In recent years, ANN technique as efficient problem-solving paradigms has been applied to many science and engineering fields, because of its significant advantages in some aspects, such as recognizing and learning the underlying relations between inputs and outputs with no need for any explicit physical relation, regardless of the problem dimensionality and system nonlinearity; and the high tolerance to data containing noise and measurement errors due to the distributed processing within the network [7,8]. On the other hand, neural networks, in particular the multi-layer feed forward neural networks, have become an effective alternative to more traditional statistical techniques for function approximation and data fitting purposes. Moreover, unlike other statistical techniques, the multi-layer networks make no prior assumptions concerning the data distribution as they can highly model non-linear functions through accurate input-output data mapping and hence can be generalized for new unseen data. These advantageous features make them attractive alternatives to statistical approaches and also to numerical models. Actually, in the last two decades, it was found from the review of literature that artificial neural networks had been widely applied to solve many complex thermal science problems [9], such as heat transfer enhancement, multi-phase flow and phase change problems in the evaporators and condensers for traditional refrigerators and air conditioning systems, as well as compact heat exchangers used in many industrial applications.

Recently, the research of oscillatory heat exchangers has attracted more attention where many studies on oscillatory flows were focused on the understanding of fluid flow and heat transfer mechanisms [1,10–13]. More recently, researchers had proposed different approaches to overcome the limitations of steady flow and characterize the heat transfer of an oscillatory heat exchanger. Particularly, some experimental work [14–17], empirical correlations [6,11,14], analytical models [1,18] and numerical studies [19–21] were carried out for hydrodynamic analyses and thermal calculations for studying the thermal behavior and measuring the performance of the heat exchanger based on oscillatory flow condition instead of using steady flow approaches in the design of thermoacoustic devices [4]. It is noteworthy that the oscillatory heat transfer is a complex process in thermoacoustic devices, such as, a standing-wave thermoacoustic refrigerator, where the heat transfer occurs between gas particles with high-amplitude acoustic standing waves and solid materials within heat exchangers located at each end of the stack, and dynamic pressure, velocity and temperature changes in the acoustic standing wave would cause a net thermoacoustic heat flow up a mean temperature gradient along the direction of sound wave propagation in the thermoacoustic core. Accordingly, the performance of heat exchangers at the two ends of stack/regenerator is considered a significant limiting factor for thermoacoustic heat flow and thus the performances of thermoacoustic systems. Hence, some researchers focused on the oscillatory heat transfer of a finned heat exchanger as an ambient heat exchanger either for thermoacoustic refrigerators [14] or pulse tube refrigerators [6] in order to estimate the Nusselt number (Nu) or oscillatory heat transfer coefficient (h) as a measure for the performance of ambient heat exchanger, subjected to different operating conditions (parameters) such as oscillating frequency and mean pressure. The experimental work conducted in [6,14] was correlated in terms of Nusselt number, Reynolds number and either Prandtl number or Valensi number in order to obtain some correlations for the heat transfer coefficient of the ambient heat exchanger. All these researches above undoubtedly provide some useful correlations as well as theoretical fundamentals of the oscillatory heat transfer for the development of thermoacoustic devices. At the same time, the results from these existing correlations with some uncertainties and lack of generalization stimulate our research interests to explore a new approach to investigate the complex oscillatory heat transfer for thermoacoustic applications. One related work [22] was to predict the Nusselt number through ANN for one oscillating annular flow with reference to four parameters, namely, kinetic Reynolds number, dimensionless amplitude, filling heights, and heat flux. The network structure in [22] was optimized to 4-5-1 configuration, and the network predictions of Nusselt number by ANN were closer to the experimental values with a deviation of about 5%.

After the successful application mentioned above to estimate the cycle-averaged Nusselt number in an annular channel subjected to oscillating flow, ANN is confirmed as a promising approach for engineer's preliminary estimation of complex heat transfer problems in the present study. Hence, one artificial neural network model will be introduced to map the relationship between the operating parameters and performance of thermoacoustic heat exchanger, and thus to provide a more accurate and practical approach to predict the response of oscillatory heat transfer coefficient to the oscillating frequency and mean pressure for one typical standing wave thermoacoustic refrigerator conducted in [14].

2. Artificial neural network model for predicting oscillatory heat transfer coefficient of one thermoacoustic heat exchanger

2.1. Physical model

For comparison, the experimental setup system with the ambient heat exchanger of the finned-tube structure in [14], was used as the physical model in the present research. It is a standing wave thermoacoustic refrigerator with a λ/4 resonator tube, driven by an acoustic driver at one end, and closed rigidly with a cone-shaped

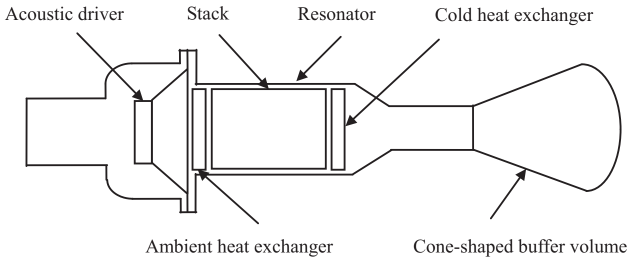

Fig. 1. Schematic diagram of a standing wave thermoacoustic refrigerator with a λ/4 resonator tube.