Application of Artificial Neural Network (ANN) method to exergy analysis of thermodynamic systems

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Abstract

Exergy is a way to sustainable development and may be defined as the maximum theoretical useful work, while exergy analysis identifies the sources, the magnitude and the causes of thermodynamic inefficiencies within each system component. In the exergy analysis of a thermodynamic system, many equations, constants, tables and assumptions are needed. In this regard, the data of any system considered should be measured by sensors and recorded to an hard disk. Thereby much more effort is needed to have accurate exergy results of the whole system along with its components.

ANN is part of Artificial Intelligence (AI), while it is capable of learning to recognize non-linear input–output relationship. By using the ANN, which was previously trained with less data, exergy results can be obtained easily including closer results. For example, in a study conducted by the authors on the exergy analysis of gas turbines, Root Mean Square Error (RMSE) values were obtained under 0.01. Definition of inputs of the ANN is very important, that effects the results and solution time. The results were solved by Fast ANN (FANN) Library, which could be implemented to C++ code and Mathlab.

The main objectives of the present study are twofold, namely (i) to apply the ANN method to exergy analysis of thermodynamic systems by presenting the performance of the ANN method and (ii) to emphasize the definition of ANN inputs. In this context, exergy analyses of some systems in the literature were reviewed. It may be concluded that most of thermodynamic systems can be trained and analyzed by using the ANN method. It is expected that this study would be very beneficial to those dealing with the intelligent systems of the future.

Keywords: Artificial Neural Network, ANN, exergy, thermodynamic system

1. Introduction

According to energy associations like Energy Information Administration (EIA), the world energy projection is commonly analyzed in transportation, industrial, residential, commercial, electric power areas. All of those areas includes small to large capacity thermodynamic systems. According to data of energy resources, costs of common energy resources are increasing due to demand from both industrial and individual facilities [1]. To decrease production cost, one of the solutions is to minimize energy consumption. This can be obtained by energy analysis which is mostly based on first law of thermodynamics. This is applicable to all energy sectors including thermodynamic systems. Furnace, Gas turbine, cogeneration system, spray dryer, heat exchanger, a heat pump system, fuel burner, ejector-
absorption heat transformer and regenerator bed are some examples to thermodynamic systems.

Another solution is the exergy analysis which is mostly focused on useful energy based on second law of thermodynamics. This is also applicable to all energy sectors which can be analyzed, mostly thermal systems.

Artificial Intelligence (AI) is simulating human brain behavior by hardware or software and ANN is a part of AI, while it is capable of learning to recognize non-linear input–output relationship. Generally ANN is a software, or code which learns (train) from a given data pack (patterns) including inputs, and outputs. ANN is primarily a multilayer feed forward network under the back propagation learning algorithm used extensively for pattern recognition [2]. ANN method explores competing hypotheses using massively parallel network consisting of non-linear elements connected by variable weights.

Previous conducted studies on the application of exergy analysis through ANN have been briefly reviewed as below.

Das et al. studied on exergy analysis of regenerator beds and they used ANN to predict the pressure drop data for unknown heat exchanger surface by analyzing similar data [3].

Park et al. implemented artificial neural networks in patterning and predicting exergy by utilizing the networks' feasibility of information extraction and self-organization [4]. Exergy results were obtained by the backpropagation algorithm on exergy of selected data. The trained mapping was able to characterize the development trend of exergy at different groups of sample sites in different time periods.

Arcaklioglu et al. investigated the performance of a vapor compression heat pump with different ratios of R12/R22 refrigerant mixtures using ANN [5]. They were used experimental data to obtain training and test data. As a result, by using ANN method they found COP values with RMS values smaller than 0.006. Arcaklioglu investigated the neural networks for calculation of performance in vapor-compression refrigeration system using refrigerant mixtures [6]. He obtained COP values with RMS error values smaller than 0.002.

In the study of Hosoz and Ertunc, authors researched applicability of ANNs to predict the performance of automotive air conditioning (AAC) systems using HFC134a as the refrigerant [7]. They developed an ANN model for the system, based on the standard back propagation algorithm. The model was used for predicting various performance parameters of the system, namely the compressor power, heat rejection rate in the condenser, refrigerant mass flow rate, compressor discharge temperature and coefficient of performance (COP). They are obtained COP values by ANN with a RMSE of 0.08.

Hosoz and Ertunc investigated the applicability of artificial neural networks (ANNs) to predict various performance parameters of a cascade vapor compression refrigeration system [8]. They setup an experimental cascade system and they tested in steady-state operating conditions. As a result they found that the ANN predictions usually agreed well with the experimental results with correlation coefficients in the range of 0.953–0.996 and mean relative errors in the range of 0.2–6.0%.

In the study of Sencan et al., ANN is used as a new approach for the determination of the thermodynamic properties of LiBr-water and LiCl-water solutions which have been the most widely used in the absorption heat pump systems [9]. They found that the coefficient of multiple determination (R2- value) between the actual and ANN predicted data is equal to about 0.999 for the enthalpy of both LiBr-water and LiCl-water solutions.

Sencan et al. investigated energy and exergy analysis of a vapour compression refrigeration systems for determining subcooling and superheating effects of environmentally safe new refrigerants [10]. They used three different refrigerants (R134a, R407c and R410a). The thermodynamic properties of the refrigerants are formulated using ANN methodology and six ANNs were trained to predict various properties of the three refrigerants. From the ANN analysis they found that condenser and evaporator temperatures have strong effects on coefficient of performance (COP) and system irreversibility.

Selbas et al. applied exergy-based thermoeconomic optimization application to a subcooled and superheated vapor compression refrigeration system [11]. All calculations were made for three refrigerants: R22, R134a, and R407c. Thermodynamic properties of refrigerants were formulated using the ANN methodology.

Sozen and Arcaklioglu investigate artificial neural networks (ANNs) technique as a new approach to determine the exergy losses of an ejector-absorption heat transformer (EAHT) [12]. In their study they focused on predicting the exergetic performance of components of an EAHT prior to its setting up in a thermal system where the working temperatures are known. In their study RMS values are found mostly below 0.03.

Sozen et al studied on an alternative approach based on ANN to determine the thermodynamic properties of an environmentally friendly refrigerant (R404a) for both saturated liquid-vapor region and superheated vapor region as numerical equations [13]. They obtained results including three dimensional graphics with temperature, entropy, pressure, specific volume and enthalpy parameters. In another study, Sozen et al. developed a new formula based on artificial neural network (ANN) technique to determine the efficiency of
flat plate solar collectors. They found that the maximum and minimum deviations 2.558484 and 0.001969, respectively.

Yoru investigated ANN Application and Exergy Analysis of a cogeneration system which operates by natural gas [14]. He obtained both energy and exergy efficiency of the whole system, he also found exergetic values by ANN.

Esen et al. reported on a modeling study of new solar air heater (SAH) system by using ANN and wavelet neural network (WNN) models [15]. In their study, a device for inserting an absorbing plate made of aluminum cans into the double-pass channel in a flat-plate SAH. They obtained as 0.0126 RMSE value for collector efficiency.

Yoru et al. applied energetic and exergetic analyses of a cogeneration (combined heat and power, CHP) system installed in a ceramic factory and in the analysis, actual operational data based on the 720 hour data pattern over one month period are utilized [16]. In another study, Yoru et al. applied the ANN method to this cogeneration system for exergetic evaluation purposes[17]. ANN trained from the data used are based on the actual operational conditions and tested. Yoru et al. also used ANN method to find exergetic analyses of gas turbines (GT) by using actual operating data of 3 GTs [18].

Mohanraj et al. applied ANN for exergy analysis of a direct expansion solar-assisted heat pump (DXSAHP) [19]. They were developed an ANN model based on backpropagation learning algorithm for predicting the exergy destruction and exergy efficiency of each component of the system at different ambient conditions. They found that the ANN predictions for exergy efficiency in the solar collector yield a correlation coefficient of 0.9514 with 0.0045 RMS values and 1.2418, respectively.

From the examples above, there are less studies on neural network based exergy analysis of thermodynamic systems in the open literature to the best of the author’s knowledge.

The main objectives of the present study are twofold, namely (i) to apply the ANN method to exergy analysis of thermodynamic systems by presenting the performance of the ANN method and (ii) to emphasize the definition of ANN inputs. In this context, exergy analyses of some systems in the literature were reviewed. It may be concluded that most of thermodynamic systems can be trained and analyzed by using the ANN method. It is expected that this study would be very beneficial to those dealing with the intelligent systems of the future.

2. Artificial neural network theory

AI systems, are developed to solve complex problems, they can learn from given examples and are able to solve non-linear problems, problems have noisy and incomplete data. They can perform predictions and generalizations at a high speed [12].

For the beginning ANN theory to solve some mechanical engineering problems there are good sources about ANN method. Main concepts of ANN is introduced by Hassoun [20], while Hertz [21] described the mathematics of ANN very thoroughly. Anderson [22] used a more psychological and physiological approach to ANN and ANN. There are popular softwares like Matlab, code packs (library) like Fast Artificial Neural Network (FANN) and many other commercial softwares.

Basically mathematical equation of an artificial neuron can be shown as below:

$$y(x) = g\left(\sum_{i=0}^{n} w_i x_i\right)$$

(1)

where $y(x)$ is one output axon, $x$ is a neuron with $n$ input dentrites $(x_0, x_1)$, $w$ is weight and $g$ is a sigmoid function. Activation function $g$ should be a simple threshold function returning 1 or 0 [23]. This single artificial neuron, simple network models and example sigmoid functions are shown in the ANN literature [23].

ANN is a network consisting of connected artificial neurons, including inputs, outputs and layers. The input and output layers contain number of neurons equal to number of input and output parameters, respectively. The number of hidden layers depends on the training algorithm.

The logarithmic sigmoid function ,

$$a = \frac{1}{1+e^{-n}}$$

(2)

and the hyperbolic tangent sigmoid function is

$$a = \frac{e^{n}-e^{-n}}{e^{n}+e^{-n}}$$

(3)

which are the most commonly used functions in multilayer networks. In the comparison of exergy destruction by ANN, the error during the learning is called root-mean square error (RMSE) and defined as follows:

$$\text{RMSE} = \left(\text{MSE}\right)^{1/2}$$

(4)

with the mean square error (MSE) given by

$$\text{MSE} = \frac{1}{p} \sum_{j=0}^{p} (t_j-o_j)^2$$

(5)

where $t$ is the target value, $o$ is the output value, and $p$ is the pattern number. RMSE gives a measure of the prediction accuracy [24].
3. Energy and exergy analysis of a thermodynamic system

Energy analysis and exergy analysis are widely used to define efficiencies of components and whole systems. Exergy is maximum amount of work, which can be produced by a system or a flow of matter or energy as it comes to equilibrium with a reference environment by reversible [25].

Basically general energy and exergy balance equations for a steady-state, steady-flow process can be given as follows, respectively,

\[ \dot{E}_{in} - \dot{E}_{out} = 0 \]  
\[ \dot{Ex}_{in} - \dot{Ex}_{out} = \dot{Ex}_{D} \]  

Specific exergy (flow exergy) is calculated by

\[ \psi = (h - h_0) - T_0 (s - s_0) + \frac{V^2}{2} + gz \]  

while exergetic efficiency is found from

\[ \varepsilon = \frac{\dot{Ex}_p}{\dot{Ex}_F} \]  

where \( \dot{Ex}_p \) is a product exergy rate, \( \dot{Ex}_F \) is a fuel exergy rate.

4. ANN application on thermodynamic systems

In the energy analysis of a thermodynamic system, mass flow of fuels (natural gas, coal, fuel oil etc.), properties of fluids (air, water, steam etc.), pressure, temperature and other parameters must be obtained and those values should be measured for different times of different conditions. For the exergy analysis of the system temperature and pressure of the environment also should be measured. Basic steps for the energy and exergy analysis of a system can be briefly defined as follows:

1. Define fuels of the whole system.
2. Define products of the whole system.
3. Define needed nodes of the whole system which can be inlet and outlet of a component (e.g. turbine inlet and outlet)
4. Obtain data of measurements (temperature, pressure, mass flow) of the nodes of systems, at least more than 10 data for the accurate solution.
5. Calculate unknown node properties (temperature, pressure, mass flow, enthalpy, entropy, energy, exergy destruction etc.)

6. Make assumptions if some parameters are still unknown, unable to calculate or unable to measure.
7. Find energy and exergy rate of fuel and product
8. Find energy loss and exergy destructions of the components
9. Find energetic and exergetic efficiency of the whole system

Basic steps for the energy and exergy analysis of a system by ANN may be described as follows:

1. For the exergy analysis include environment temperature and pressure as input if they varies.
2. Define exergetic outputs (product exergy, fuel exergy, exergy destruction, exergetic efficiency, exergy input, exergy output etc.)
3. Design ANN for the defined inputs and outputs. (mostly feed forward network under the back propagation learning algorithm, sigmoid function, at least 3 layers, 3 hidden neurons)
4. Modify all inputs and output values between 1 (max) and 0 (min) for the sigmoid function.
5. Train network by modified inputs and outputs (start with inputs less then 10, 1 output, 3 layers, 2 or 3 hidden neurons, 0.001 error)
6. Test network with same results and other results.
7. Try to get much closer RMSE values by changing / adding input, layers, number of hidden neurons, sigmoid function etc.

Simplified ANN model for the exergy analysis of a thermodynamic system is shown in Figure 1. The definition of which ANN inputs needed is the most important thing for the prediction of exergy values. Distribution of the input parameters over the range is important for the prediction performance.

Generally multilayer feed forward network under the back propagation learning algorithm is used to predict...
exergy results from input data. Sufficient number of training samples over the range must be taken into account to obtain an accurate ANN model on the whole range of input parameters.

In the ANN analyses of Yoru et al., number of patterns (24 to 718 patterns), number of inputs (14 or 18 inputs), number of outputs (1 or 2 outputs), layers (2,3,4 layers), hidden neurons and desired error values (\(10^{-4}\) to \(10^{-6}\)) are considered. The exergy destruction rates obtained from the trained network are compared with those from the thermodynamic equations, as illustrated in Figure 2. Mean exergy destruction rate of the system is found to be 60,955 kW from from the thermodynamic equations and it is obtained 61,001 kW from ANN, which means that the difference between two is only 46 kW (0.075%).

ANN is also able to calculate the exergetic efficiency of a system by the chosen proper inputs as as shown in Figure 3 (RMSE=0.005385). The error associated with exergetic efficiency values is found to be 0.29%.

Conclusion

By the light of our studies and previously conducted studies, ANN method can be successfully applied to exergy analysis of a thermodynamic system by using actual operational data. This data should have at least 10 series of inputs (patterns) and these patterns should be measured in different conditions. Using this data, ANN may able to train successfully, the more data you have the
more accurate ANN you have. Also if the small data intervals (e.g. 1 s., 1 h.) are chosen the much more accurate exergy values can be obtained.

Software of the systems can be easily developed to real-time energy and exergy analysis of the system by using ANN method. Thereby, system may automatically switch to better exergetic conditions or operators may set system manually.

It is expected that this study would be very beneficial to those dealing with the intelligent systems of the future.

10. References


