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Evaluation of Thermodynamic Analysis of Solar Energy Systems Integrated into Sustainable Buildings with Artificial Neural Network: A Case Study

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Abstract

With the increasing concern on the environment and climate change, scientists focused on the way in which new structures, especially in the field of energy. In this sense, the concept of sustainable buildings is developing day by day in terms of energy efficiency. The sustainable building concept identifies five objectives which are resource efficiency, energy efficiency, prevention of pollution, harmonization with the environment; and also using integrated and systemic approaches. To increase energy efficiency in buildings, the integration of Solar Energy Systems into buildings attaches importance in terms of sustainable engineering designs. Evacuated Tube Heat Pipe (ETHP) solar energy systems are also noteworthy in this regard. This paper presents the results of an experimental study that is an ETHP solar collector system. ETHP systems are an alternative solar energy system to low-efficiency planary collectors. Only water was used to avoid losses in the heat transfer from the fluid to the fluid. Water is inserted in the vacuum tube in order to improve the rate of heat transfer, such that the mode of heat transfer from the inner surface of the vacuum tube to the heat pipe becomes convection via the water, as well as conduction through the installed. The exergy efficiency of the ETHP system was calculated as 32.94%. For a long time, artificial neural networks (ANN) have been widely applied in energy efficiency for modeling and optimization of various processes. In the field of processing, recent studies confirm the validity and effectiveness of using ANNs as promising and most powerful computer modeling techniques. Within the scope of this study, exergy efficiency was evaluated on the developed Artificial Neural Network algorithm. The effect rates of parameters such as pressure, temperature, and ambient temperature affecting exergy efficiency were calculated. Finally, significant findings obtained were evaluated in terms of thermodynamics rules.

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1. Introduction

The need for energy has always been a significant issue for humanity, technology, ecology, and sustainability. However, it is expected that the energy need will continue to be important in the future. There are two primary sources of energy available to meet energy needs. These; fossil fuels and alternative energy sources. Nowadays, the continuous increase in energy demand, global warming, the destruction of the ozone layer, and environmental pollution brings alternative energy sources to the forefront instead of fossil fuels. However, currently, fossil resources are the first in energy production. Due to the carbon content of the fossil fuels, CO_2, NoX, and halocarbon gases are released into the atmosphere as a result of the combustion process, which causes global warming as a result of combustion. The United Nations Secretariat of Climate Change works worldwide on the issue of global warming. Accordingly, the Kyoto Protocol was signed by 192 countries, and the Paris agreement was signed by 179 countries [1-3].

Renewable energy sources, especially solar energy, have the potential to meet the global energy demand without causing environmental pollution. For most people all over the world, solar energy is evaluated as a primary energy source for the future. Solar energy can be exploited by two different methods: direct electricity generation or thermal energy generation. Solar collectors are divided into three different methods according to their working temperatures and design differences such as flat plant collectors (FPCs), evacuated tube collectors (ETCs) and concentrating collectors (CCs) [4]. ETCs operate at medium temperature (50°C-200°C), and due to the vacuum inside the tube, the energy losses with heat transfer are less than the FPCs. Therefore, the efficiency of ETCs is higher than in FPCs. There are two types of ETCs that use working fluid water, which are direct flow ETCs and heat pipe ETCs [5, 6].

In this context, the modeling of energy issues is a remarkable issue in terms of energy production and consumption for engineers. Thus, in several areas of application, these models provide efficient planning of energy policies. Energy policy planning can only be done by estimating future data by analyzing past and current data [7-9]. In engineering models, it is thought that the right choices are made between the existing technologies, and also, the sector is used efficiently to meet the energy demand. In this sense, the costs are minimized by increasing systemic productivity as a requirement. In terms of industry, it is known that input-output modeling of each sector is based on existing or projected production functions due to business areas [10]. In this context, it is necessary to define the correct inputs and outputs in terms of efficiency and to make predictions with appropriate models. For this reason, artificial neural networks are essential in terms of modeling to save time and cost by applying efficiency methodologies.

Artificial neural networks (ANN) are systems and computational devices to benefit from some organizational principles similar to the human brain. As in the human brain, artificial neural networks are also capable of learning and remember the data used to train the system. Thus, ANN models were developed to handle practical problems and became extremely popular. In any problem, the data in the input units represents the problem presented to the network; and the data in the output units represent the calculation results [11, 12]. Therefore, instead of trying to solve many different problems with complex differential equations, faster and simpler solutions can be obtained by using equations derived from the ANN model. As a result, the advantages of ANN according to the classical methods are speed, simplicity, and current capacity in terms of learning from the examples.

For this reason, it is seen that there has been an interest in the use of ANN in energy systems, and studies have been published in the last decade. As an example, They have used ANN methodology for predicting osmotic pretreatment based on the energy and exergy analyses in microwave drying of orange slices [13]. Also, in 2007, Sencan, 2007 [14] introduces the study of the performance analysis of the ammonia-water absorption refrigeration system by using Artificial Neural network. Kalogirou, 2000 [15] investigated applications of ANN for energy systems. ANNs have been applied by the author in the field of solar energy. The performance of the selected model is tested by the history data of the past and the performance of the actual system. Ghritlahre and Prasad, 2018 [16] evaluated the application of the ANN technique to predict the performance of solar collector systems. The evaluations presented in this study show that the ANN technique is a very suitable tool for estimating the performance of solar collector systems.

2. Material and Methods

In this section, the solar energy system, in terms of thermodynamics, is introduced. First of all, the solar energy system is determined, and the thermodynamic model belonging to the system is set up. In the next section, the Artificial

Neural Network system with different algorithms/architectures are introduced. In Section 2.4, the developed ANN model, basic descriptions are given.

2.1. System Description

In this study, the evacuated tube heat pipe collectors are investigated. The system consists of 4 panels, and each panel has 27 evacuated tube heat pipes and has a total of 108 evacuated tube heat pipes. The pipes consist of two intertwined glass and vacuumed between the glasses. Water is used as a working fluid in the system. The water enters the system from the bottom of the collector, emerges from the collector in the vapour phase with the radiation energy, and enters the hot storage tank. It is separated from the system for use after storage tank. In figure 1 shows the heat pipe vacuum tube solar collector installed on the roof of the engineering faculty of the Istanbul Gedik University for experimental study.

Figure 1. The evacuated tube heat pipe collector

2.2. Thermodynamic Analysis

This section presents the thermodynamic analysis of ETHP collector. The liquification unit has been investigated according to the first and second law of thermodynamics. When the thermodynamic analysis of the cycle was carried out, energy analysis in the first law, the exergy destruction in the second law and exergy efficiency were examined. The energy analysis shows the improvement amount of the process. The results of the energy analysis reveal the efficiency of energy use in certain parts of the process and ensure that the efficiency and process parameters are compared to the values that are currently available in the most modern plants. The exergy of a form of energy or a substance is a measure of the benefit or quality or potential that may cause change. Distinctly energy, exergy is protected only during ideal operations and is destroyed by irreversibility in actual operations [17, 18]. Input solar radiation rate is found by;

$$\dot{En}_{solar} = DNI * \rho_{ref} * \rho_{rec} * \varepsilon_{rec} * A_{ref} * A_n * A_{rec} \quad (1)$$

or

$$\dot{En}_{solar} = \dot{m}c_p(T_{out} - T_{in}) \quad (2)$$

Where DNI is the direct normal irradiance measured in a plane normal to the sun, ρ_{ref} is reflectance of the mirror,

ρ_{rec} is an absorber of the receiver, ε_{rec} is emissivity of the receiver, A_{ref} is a reflector area, A_n is reflector numbers and A_{rec} is the receiver area, respectively. Where $\dot{m}$, c_p, T_{out} and T_{in} are mass flow of water, the specific heat of water, the temperature of output water and temperature of input water, respectively. The energy loss in the system is due to convection and radiation. Total energy loss is found by;

$$\dot{En}_{loss} = \dot{En}_{loss,conv} + \dot{En}_{loss,rad} \tag{3}$$

Where $\dot{En}_{loss,conv}$ and $\dot{En}_{loss,rad}$ are energy loss with convection and radiation, respectively.

$$\dot{En}_{loss,conv} = hA_{gs}\left(T_{surf} - T_{air}\right) \tag{4}$$

Where h, A_{gs} and T_{surf} are heat transfer coefficient, heat transfer surface area of the glass cover and glass cover surface temperature, respectively.

$$h = \frac{kNu}{L} \tag{5}$$

Where k and L are thermal conductivity and characteristic length, respectively. The Nusselt number (Nu) and the Rayleigh number (Re) are defined as;

$$Nu = \left[0.6 + \frac{0.387(Ra)^{1/6}}{\left\{1+\left(\frac{0.559}{Pr}\right)^{9/16}\right\}^{8/27}}\right]^2 \tag{6}$$

Where Ra and Pr are Rayleigh number and Prandtl number, respectively.

$$Ra = \frac{g\beta\left(T_{surf}-T_{air}\right)D^3}{\nu^2}Pr \tag{7}$$

Where g is gravity, D is the diameter of the glass cover and ν^2 kinematic viscosity, respectively.

$$\dot{En}_{loss,rad} = \varepsilon\sigma A_{gs}\left(T_{surf}^4 - T_{sky}^4\right) \tag{8}$$

Where ε is the emissivity of absorber tube, σ is the Stefan-Bolztmann constant and T_{sky} is the sky temperature, respectively. The water exergy change is defined as;

$$\dot{Ex}_{water} = \dot{Ex}_{out} - \dot{Ex}_{in} \tag{9}$$

Where $\dot{Ex}_{water}$ is the water exergy change, $\dot{Ex}_{out}$ is the exergy of output water and $\dot{Ex}_{in}$ is the exergy of input water, respectively. The exergy output of water is found;

$$\dot{Ex}_{out} = \dot{m}c_p\left[\left(T_{out} - T_{air}\right) - T_{air}\left(\ln\left(\frac{T_{out}}{T_{air}}\right)\right)\right] \tag{10}$$

Where $T_{out}$is the temperature of output water and T_{air} is the ambient temperature, respectively. The exergy input of water is found;

$$\dot{Ex}_{in} = \dot{m}c_p\left[(T_{in} - T_{air}) - T_{air}\left(\ln\left(\frac{T_{in}}{T_{air}}\right)\right)\right] \quad (11)$$

Where T_{in} is the temperature of input water. The input solar radiation exergy rate is found;

$$\dot{Ex}_{solar} = \dot{En}_{solar}\left(1 + \frac{1}{3}\left(\frac{T_{air}}{T_{sun}}\right)^4 - \frac{4}{3}\left(\frac{T_{air}}{T_{sun}}\right)\right) \quad (12)$$

Where T_{sun} is sun temperature. Exergy loss is as exergy loss with convection and radiation are found;

$$\dot{Ex}_{loss} = \dot{Ex}_{loss,conv} + \dot{Ex}_{loss,rad} \quad (13)$$

Where $\dot{Ex}_{loss,conv}$ and $\dot{Ex}_{loss,rad}$ are exergy loss with convection and radiation, respectively.

$$\dot{Ex}_{loss,conv} = \dot{En}_{loss,conv}\left(1 - \frac{T_{air}}{T_{surf}}\right) \quad (14)$$

$$\dot{Ex}_{loss,rad} = \dot{En}_{loss,rad}\left(1 - \frac{T_{air}}{T_{surf}}\right) \quad (15)$$

The exergy destruction rate of the system can be found in the following equation;

$$\dot{Ex}_{dest} = \dot{Ex}_{in} + \dot{Ex}_{solar} - \dot{Ex}_{out} - \dot{Ex}_{loss} \quad (16)$$

The exergy efficiency of the overall system;

$$\eta_{II} = \frac{\dot{Ex}_{water}}{\dot{Ex}_{solar}} \quad (17)$$

2.3. Artificial Neural Networks (ANN)

The computer system, which can characterize problems such as human intelligence and processes by having the capability of learning, reasoning, and self-correction, is called Artificial Intelligence (AI). Artificial intelligence consists of two main branches, expert systems, and artificial neural networks. Artificial neural networks, which have been discovered some 50 years ago but have only been involved in software applications for the last 15 years, give good results in solving many problems. In particular, it is good to use artificial neural network algorithms for incomplete data sets, fuzzy or incomplete information, and relatively complex and poorly defined problems [14].

The most common used architectures are General Regression Neural Networks (GRNN), Probabilistic Neural Networks are (PNN), Back Propagation Neural Network (BPNN) and the Group Method of Data Handling (GMDH). The BPNN has been applied with great success to model many phenomena in the field of engineering. Each neuron in a layer receives weighted inputs from the neurons in the previous layer and then processes its output through the links to the neurons in the following layer. Thus, each link is assigned a weight, which is a numerical estimation of the link strength [11]. For example, GRNN, an ANN algorithm, is a three-layer network with a latent neuron for each exercise model, in addition to the total number of neurons equal to the sum of the number of inputs and outputs [19]. The performance of the datasets based on ANN is based on some statistical criteria such as multiple determination coefficient and coefficient of variation.

2.4. Developed ANN Model

With the developed model, it was determined which variables to be used as network inputs, and outputs, and the minimum and maximum values were calculated for each variable. According to this, Radiation (I), Mass (m) and

Ambient temperature (Tair) are taken into consideration as input parameters. The Exergy (kJ/kg) of the system is the output parameter that is used in the developed ANN model. Besides the training set, also it is extracted a test set and a production set of data from the training patterns. We use the N percent (Test Set), M percent (Production Set) as randomly. According to this, 30% of the data taken to make a test and 15% of the data taken to make a forecast, so that %55 of the data used at the training phase. As a result of this, 121 data used in the training, 66 data used in the testing, and 33 data used as forecasting.

Different ANN architectures which are PNN, GRNN, Probabilistic, etc. are used to evaluate if the data fit the architecture. Finally, the recurrent network with hidden layer feedback is chosen as the network architecture of the BPNN model. Two neurons are used in the hidden slabs; Logistic is used as a scale function algorithm, the learning rate, and momentum impacts are taken as 0.2 (Figure 2).

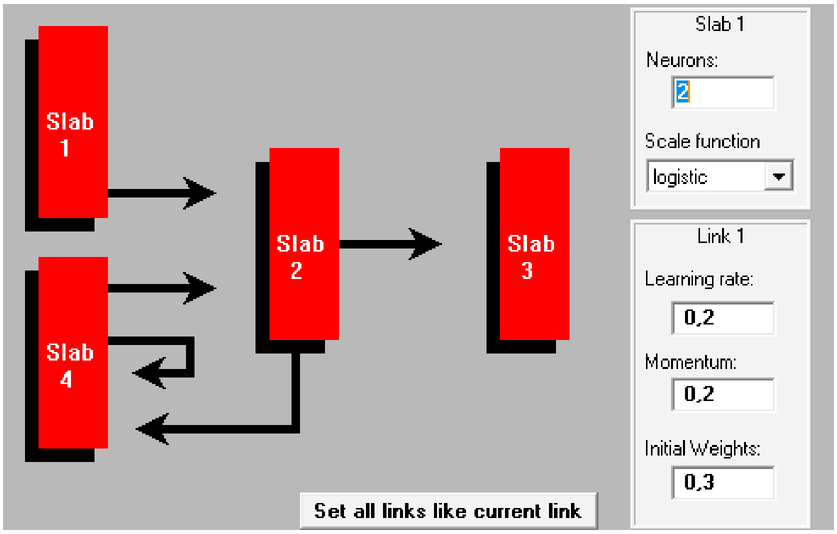

Figure 2. Developed the BPNN model.

3. Results and discussion

The primary purpose of this study is to assess the performance of the evacuated tube heat pipe solar collector at relatively medium inlet temperatures. In table 1, table 2 and table3, the results obtained from Thermodynamic equations produced by using exergy analysis are given together with the thermodynamic outputs of the ETHP system given.

Table 1. Thermodynamic analysis results of the ETHP system

Radiation (W/m^2)	Ambient Temperature (K)	Mass flow (kg/s)	Exergy efficiency (%)
100	291.2	0.1	0.006794
⋮	⋮	⋮	⋮
1000	291.2	0.1	0.06737
750	291.2	0.01	0.3357
⋮	⋮	⋮	⋮
750	291.2	0.19	0.02769
750	290	0.1	0.05548
⋮	⋮	⋮	⋮
750	305	0.1	0.003068

Table 1 shows the main results obtained from the exergy analysis of the ETHP system. When Table 1 is examined, it is shown that the lowest exergy efficiency in the system measured as 0.3068% depending on the increase in the ambient temperature. In addition, the highest exergy efficiency calculated as 33.57% in the case of the lowest mass flow (0.01 kg / s).

In the learning phase, training and testing are calculated according to the minimum and last average errors. Last average error from BPNN algorithm reaches almost zero (0.0006). In GRNN training phase smoothing factor is taken as 0.3 and after the training process, it reaches to the value 0.01. However, the success rate of the developed GRNN model was %38, and the output variables have essential errors. N the other hand, BPNN gives a better success rate, which is more applicable (%62). In Figure 3, it is seen that the errors in each hidden layer closer to the zero and the curve is meaningful in terms of ANN literature.

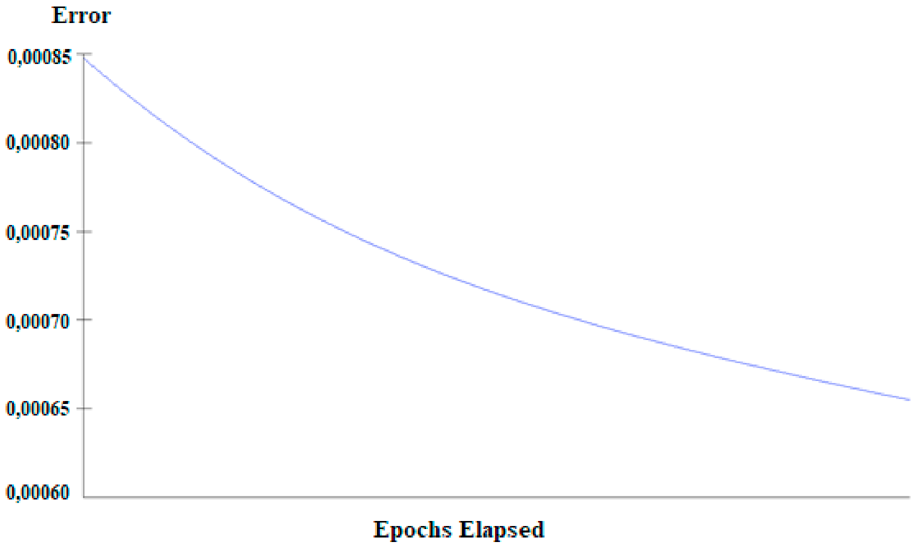

Figure 3. Errors – Epochs Elapsed relationship of developed BPNN model.

In this study, when the ANN model that examined was evaluated using various standard statistical performance evaluation criteria and mathematical formulations is trained, in BPNN training cycle, for the R squared value and correlation coefficient, the best is obtained from a network with two hidden layers. As a result, the effect of Radiation (I) is 0,04237, Mass (m) is 0,07473, and the Environmental temperature (Tair) is 0,02935 on the exergy. In short, the effect of Mass (m) is almost two times higher than the radiation and environmental temperature. This gives meaningful findings in terms of thermodynamics.

4. Conclusion

In this study, artificial neural networks, which are growing exponentially and used in many studies by many scientists, programmers, and engineers, have been used in the exergy efficiency of solar energy systems according to the case data.

The study contains calculations of the exergy values of the solar energy system based on the ANN approach. The main conclusions that can be drawn from the present are summarized that the 220 data of experimental measurements obtained from the evacuated tube heat pipe system have been found via the Engineering Equation Solver (EES) program. These data are based on mathematical formulations of thermodynamics to calculate exergy efficiency. The form of the ANN was developed by using BPNN algorithm with the observed data for future estimation. A meaningful forecast tool demonstrated by developing an ANN approach model. In this sense, ANN can be successfully implemented for modeling and forecast of solar energy systems that are integrated into sustainable buildings. The use of ANN is preferred when enough and valuable data present because it does not need too many parameters for future estimates. In short, the contribution to the literature on planning, determination of energy policies, and energy efficiency are expected.

- The change of the exergy efficiency of ETHP system depending on the changing physical parameters

(Radiation, ambient temperature, and mass flow) was investigated.

- The highest exergy efficiency as 33.57% was obtained at the lowest mass flow case (0.01 kg/s), while the lowest exergy efficiency as 0.3068% was calculated at the ambient temperature increased (0.01 kg/s).
- When the ambient temperature and mass flow rate was increased, the exergy efficiency was decreased.

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