

Performance Evaluation Criteria of Heat Exchanger Tanks Based on the Analysis of Second Law of Thermodynamics

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Abstract-The present paper investigates the fundamental thermodynamic laws and heat exchanger tank. It introduces the entropy and examines the second law of thermodynamic analysis for this type of exchanger. The methodology involves examining heat exchanger tank under different laboratory conditions including the power of heat element inside the tank, mass flow rate of cooling water of tank wall and the mixer speed inside the tank as variables. The data for the water temperature inside the tank and output water were obtained after cooling the tank wall. The entropy generation rate was then drawn and the optimal performance criteria of the heat exchanger tank and its optimal range were evaluated by minimization of entropy via the second law analysis. This was undertaken to increase the efficiency and decrease energy consumption. The results indicate that when the mass flow rate of input cold water, power of heat element and the mixer speed were respectively controlled in their possible minimum measures, the system tend to perform in optimal conditions according to the second law of thermodynamics.

Keywords- the second law of thermodynamics, heat exchanger tank, entropy.

I. INTRODUCTION

Change in heat transfer rate to temperature in a reversible process is called entropy or irregularities, which is known as the system property. If the adiabatic process is reversible, its entropy change would be zero that is called steady entropy process or isentropic. And if the process is irreversible adiabatic, the entropy would increase. The process of heat exchange between two fluids with different temperatures separated by a solid wall is found in many engineering applications. Heat exchanger conducts this process. Exchanger tank is one of the types that is universally used in oil and gas industry, petrochemical and power plants, coolers and heaters as well as food industry.

The thermodynamic methods for energy optimization as a powerful tool can be focused on according to the following two criteria:

- A criterion for performance evaluation in entropy and its minimization.

- A criterion that considers the exergy and its maximization as the performance evaluation. Both criteria have been explained in various studies with some advantages, features and limitations, some of which are described as follows:
- Bejan discussed the analysis of the second law of thermodynamics in heat transfer and thermal design, generated entropy via heat transfer and fluid flow, as well as the minimization of generated entropy [1], [2], [3].
- Yilmaz *et al.* examined the performance evaluation criteria of heat exchangers based on the analysis of second law of thermodynamics [4].
- Hepbasli conducted a practical and general review of exergy analysis of thermodynamic machines as well as an estimation and evaluation of renewable energy in future [5].
- Gong *et al.* stated the economic and technical optimization of processes in environment conditions by exergy [6].
- Naphon evaluated the analysis of second law in the heat transfer of horizontal concentric tube heat exchanger [7].
- Ozelik optimized the shell and tube heat exchangers by genetic algorithm using exergy analysis [8].
- Paniagua *et al.* offered a new simple method for estimation of exergy loss in heat exchangers [9].
- kakac *et al.* designed heat exchangers and determined their price [10].
- Shukuya *et al.* published an introduction to the concept of exergy [11].
- Zhu combined the exergy analysis with pinch technology for processes [12].

By examining the heat exchanger tank, the present study is aimed at thermodynamically optimize the heat transfer using the second law of thermodynamics. Optimization of every process decreases the energy loss and increases the efficiency. In contrast, lack of optimization increases both the costs and

pollution rate. Therefore, it is expected that the thermodynamic optimization of heat exchanger tank and also finding the optimal range of each parameter would reduce the energy loss and costs and help the environmental health.

II. FUNDAMENTAL RELATIONS AND CONCEPTS

One of the most important concepts in thermodynamic studies is the concept of energy. Indeed, thermodynamics can be known as the science of energy. One of the most important thermodynamics relations is the mass conservation law or continuity equation:

$$\left(\frac{dm}{dt}\right)_{c.v} + \sum_e \dot{m}_e - \sum_i \dot{m}_i = 0 \quad (1)$$

Where m stands for mass, t for time and \dot{m} for the mass flow rate. In addition, (c.v.) is the control volume, (c.s.) the control surface, (out) or (e) the output and (in) or (i) represent the input in the whole article.

A. The first and second laws of thermodynamics

The first law of thermodynamics, also known as the energy conservation law, is fundamental for the relations between energy interactions and its various shapes. Based on the experiments, the first law of thermodynamics states that energy cannot be created or destroyed but only can be transformed from one form to another. This law cannot be mathematically proved; however, no natural process or phenomenon has violated the first law of thermodynamics. The first law for the control volume is as follows:

$$\dot{Q} - \dot{W} = \left(\frac{\partial U}{\partial t}\right)_{c.v} + \sum_e \dot{m}_e \left(h + \frac{v^2}{2} + gz\right) - \sum_i \dot{m}_i \left(h + \frac{v^2}{2} + gz\right) \quad (2)$$

Where \dot{Q} stands for the heat transfer rate, \dot{W} for the performed work rate, U for the internal energy, \dot{m} for the mass flow rate, h for the enthalpy, v for the speed, t for the time, g for the gravity acceleration and z for the height.

Maintaining the quality of energy is of great importance for engineers. The second law of thermodynamics is a good measure for determining the quality and loss rate of energy during the processes. The second law of thermodynamics is founded upon the experimental observations. There are two classical expressions for the second law known as the Kelvin - Planck and Clausius which are both equivalent of one another. The second law as the principle of entropy increase for the control volume is stated as follows:

$$\left(\frac{dS}{dt}\right)_{c.v} + \sum_e \dot{m}_e s_e - \sum_i \dot{m}_i s_i = \sum_{cs} \frac{\dot{Q}}{T} + \dot{S}_{gen} \quad (3)$$

Where, S stands for the entropy, \dot{m} for the mass flow rate, \dot{Q} for the heat transfer rate, T for temperature and \dot{S}_{gen} for the rate of generated entropy.

B. Heat exchangers

Heat exchangers are devices that provide the flow of thermal energy between two or more fluids in different

temperatures and are applied in many fields including, electricity production, environmental engineering, unused heat recovery, air conditioning, refrigeration, oil and petrochemical, astronomy and also in manufacturing and production process, chemical process and food industries. There are two approaches for analyzing the heat exchangers: the Logarithmic Mean Temperature Difference (LMTD) method for design problems (determining the surface of heat exchange) and the Effectiveness-Number of Transfer Units ($\epsilon - NTU$) method for analytical problems (finding the fluid's output temperatures). In the present study, the heat exchangers are firstly classified as follows and finally, the heat exchanger tank will be studied:

- Classification based on the type and hot and cold fluid and their contact: heat transfer and recovery types; direct and indirect contact.
- Classification based on the exchanger's mechanical construction and their structure: double-tube, shell and tube and spiral tube heat exchangers; gasket and spiral plate and lamella heat exchangers; fin heat exchangers including fin-plate and tube-plate heat exchangers.
- Classification based on the flow direction of hot and cold fluid: co-current (flow), counter-current and cross-current heat exchangers.
- Classification based on the mechanism of heat transfer between the cold and hot fluid: single phase convection on both sides; single phase convection on one side; two phase convection on the other side; and finally, two-phase convection on both sides.

C. Heat exchanger tank

Heat exchanger tank, similar to a simple reactor, has an insulated cylindrical tank with water input and output, in which there exist water pipes, heat element and a mixer. Along with increasing the temperature of tank's water by the heater, the tank's wall can be cooled by its surrounding spiral pipes, the input water mass flow rate of which is adjustable. The input and output temperature of water for cooling is displayed. The power of heat element and the mixer speed are changeable for controlling the temperature of tank's water and uniforming the water, respectively. Nevertheless, the temperature of heater and tank's water is displayed on the exchanger.

D. Entropy

The concept of energy and entropy are respectively deduced from the first and second laws of thermodynamics. Entropy is a quantitative property the physical description of which is difficult. Unlike energy, entropy is a non-conservative property and there is nothing as the entropy conservation law. Clausius inequality, introduced by the German physician Clausius in the form of following relation, has significant results in thermodynamics:

$$\oint \frac{\delta Q}{T} \leq 0 \quad (4)$$

Q denotes the heat transfer and T the absolute temperature. This inequality is correct for all reversible and irreversible cycles including the refrigeration cycles. Clausius inequality is the result or consequence of the second law of

thermodynamics. The equal sign in this inequality is for the general or internal reversible cycles and the unequal sign is for irreversible cycles. Since the above integral for all reversible routes between the state 1 and 2 is the same, it is thus concluded that this is an independent quantity of the routes and is only subordinate to the terminal states which makes it a property. This property is called entropy which is shown with S. The entropy differential ds as a property of the matter is defined as follows (rev index denotes the reversible state):

$$ds = \left[\frac{\delta Q}{T} \right]_{rev} \quad (5)$$

T is the absolute temperature in a border at which the differential heating dQ is exchanged between the system and its surroundings. Considering the entropy definition, the second law is stated as follows (f & i indices denote the final and initial states, respectively):

For the process:

$$\int_i^f \left[\frac{\delta Q}{T} \right]_{rev} = S_f - S_i \quad (6)$$

For the system:

$$\frac{dS_{sys}}{dt} = \frac{\dot{Q}}{T} + \dot{S}_{gen} \quad (7)$$

And for the control volume:

$$\left(\frac{dS}{dt} \right)_{c.v} + \sum_e \dot{m}_e s_e - \sum_i \dot{m}_i s_i = \sum_{cs} \frac{\dot{Q}}{T} + \dot{S}_{gen} \quad (8)$$

Where T stands for the absolute temperature, S for the entropy, t for time, \dot{m} for the mass flow rate, \dot{Q} for the heat transfer rate and \dot{S}_{gen} for the rate of generated entropy.

E. The principle of entropy increase

The principle of entropy increase can be considered as a comprehensive and quantitative expression of the second law for thermodynamics from a macroscopic point of view. The entropy increase suggests that only those processes can occur during which the net entropy change of the system and environment is increased (or remains stable):

$$ds \geq \frac{\delta Q}{T} \quad (9)$$

The equal and unequal signs in the above relation are respectively for the reversible and irreversible process. Entropy is an extended property and thus, the total entropy of a system equals the sum of component's entropies. An isolated system (adiabatic closed system) can contain an unlimited number of subsystems. Therefore, any system and its surrounding can be considered as two subsystems of an isolated system, the entropy change of which during a process is the total entropy change of that system and its surroundings which equals the entropy generation; because, an isolated system contains no entropy transfer. Thus, the principle of entropy increase is stated as follows:

For the system:

$$\Delta S_{net} = S_{gen} = S_{total} = \Delta S_{sys} + \Delta S_{sur} \geq \quad (10)$$

For the control volume:

$$\left(\frac{dS}{dt} \right)_{c.v} + \left(\frac{dS}{dt} \right)_{surr} \geq 0 \quad (11)$$

Where ΔS_{net} stands for the net entropy change, ΔS_{sys} for the system entropy change, ΔS_{surr} for the surrounding entropy change, S_{gen} for the generated entropy and S_{tot} for the total entropy. The equal and unequal signs are respectively for reversible and irreversible processes. Since no real process is reversible, it can be stated that some of entropy is generated in every process and the more irreversible the process, the more the generated entropy during the process. Therefore, the world entropy that can be considered as an isolated system is continuously increasing. The principle of entropy increase does not state that a system's entropy cannot decrease. However, the entropy change of a system in a process can be negative, but its generation cannot be. The principle of entropy increase can be summarized as follows:

$$S_{gen} = \begin{cases} > 0 & \text{irreversible process} \\ = 0 & \text{reversible process} \\ < 0 & \text{impossible process} \end{cases} \quad (12)$$

F. Entropy transfer methods

A system's entropy change over a process is defined as the generated entropy in that process in addition to entropy transfer. There are two mechanisms for the entropy transfer: heat and mass transfer (while the energy is also transferred through work).

1) Entropy transfer via heat transfer

The input and output heat transfer to the system lead to an increase and decrease in entropy, respectively. Indeed, the only way to decrease the entropy of a constant mass is to expulse the heat. The ratio of heat transfer Q in one place to the absolute temperature T in that place is called the entropy flow or entropy transfer. The heat and entropy transfer directions are the same, because the absolute temperature T is always a positive quantity. The entropy transfer via heat is as follows which is zero for adiabatic systems:

$$0 = \frac{\dot{Q}_k}{T_k} \dot{S}_{heat} \quad (13)$$

It should be noted that the work lacks any entropy and cannot transfer it.

$$0 = \dot{S}_{work} \quad (14)$$

According to the first law of thermodynamics, there is no distinction between the heat and work transfer and they are considered as being equal. However, this distinction becomes obvious in the second law of thermodynamics. The heat transfer is a type of energy interaction accompanied with the entropy transfer. The work is the same interaction without any entropy transfer. This means that no entropy is exchanged in the work interaction of system and its surroundings.

2) Entropy transfer via mass

Mass contains both energy and entropy. The rate of energy and entropy of a system is proportionate to the mass flow. The entropy transfer via mass flow is calculated as follows:

$$\dot{m}s = \dot{S}_{mass} \quad (15)$$

When the mass m enters a system, the system entropy S increases and also decreases per output mass. Closed systems do not contain any mass flow and thus, do not have the mass-accompanied entropy transfer.

III. THE SECOND LAW ANALYSIS FOR EXCHANGER TANK

Most of the devices we use including, turbines, compressors and exchangers work with a steady flow and thus, do not have any entropy change in time. Therefore, they follow the relation of entropy balance for a steady flow. The entropy balance relation (the second law of thermodynamics) for a control volume in steady state –steady flow conditions is stated as follows:

$$\sum \frac{\dot{Q}_k}{T_k} + \sum \dot{m}_i s_i - \sum \dot{m}_e s_e + \dot{S}_{gen} = 0 \quad (16)$$

Irreversibilities always increase the system's entropy and its generation is a criterion for the generated entropy by these effects in a process. The entropy generation in a reversible process is zero and thus, the system's entropy and entropy transfer are the same. Given the second law, the generated entropy in the control volume in steady state-steady flow conditions is stated as follows:

$$\dot{S}_{gen} = \sum_e \dot{m}_e s_e - \sum_i \dot{m}_i s_i - \sum \frac{\dot{Q}_k}{T_k} \quad (17)$$

The above relation only shows the rate of generated entropy within the system boundary, rather than the generated entropy due to the external irreversibilities outside the system boundary. Therefore, a process for which $S_{gen} = 0$ is internally reversible, but not necessarily totally reversible (k index in above relation denotes the place of heat transfer).

From the energy conservation law (the first law) in steady conditions and regardless of the potential and kinetic energy, we have:

$$\dot{Q} - \dot{W} = \dot{m}_e h_e - \dot{m}_i h_i = \dot{m} (h_e - h_i) \quad (18)$$

Now the energy balance for an exchanger tank in order to find the rate of heat loss is conducted as follows:

$$\dot{Q}_{loss} - \dot{W}_{element} - \dot{W}_{mixer} = \dot{m} (h_{out} - h_{in}) \quad (19)$$

Considering the mass conservation law for the steady state and given the fact that since the rate of heat loss is directed toward the outside of control volume, a negative sign is multiplied in \dot{Q}_{loss} and it emerges with a positive sign in the final relation:

$$\dot{m}_{in} = \dot{m}_{out} = \dot{m} \quad (20)$$

$$\dot{S}_{gen} = \dot{m}s_{out} - \dot{m}s_{in} - \frac{\dot{Q}_{loss}}{T} \quad (21)$$

The following relation is obtained for the rate of generated entropy in a heat exchanger tank using the mass conservation law (continuity equation), energy conservation law (the first law) and entropy balance (the second law):

$$\dot{S}_{gen} = \dot{m} (s_{out} - s_{in}) - \frac{\dot{Q}_{loss}}{T} \quad (22)$$

$$\dot{Q}_{loss} = \dot{W}_{element} + \dot{W}_{mixer} + \dot{m} (h_{out} - h_{in}) \quad (23)$$

Where \dot{S}_{gen} stands for the rate of generated entropy, \dot{m} for the mass flow rate, h for the enthalpy, S for the entropy, T for the temperature of exchanger tank, $\dot{W}_{element}$ for the power of heat element (heater), \dot{W}_{mixer} for the mixer power and \dot{Q}_{loss} for the heat loss transfer rate from the surface control (exchanger tank wall).

IV. DISCUSSION AND ANALYSIS ON DIAGRAM

By examining the heat exchanger tank in laboratory and considering three parameters of mixer speed, power of heat element and the cold water's mass flow rate (for cooling the tank's wall) as the change parameters and registration tank's water temperature and the output cooling water, the rate of entropy generation (per minute in a 5 min period) was calculated and shown on the diagram. The following issues should be considered, however:

- Temperature of the input water and environment is considered to be 298 Kelvin.
- The amounts of enthalpy and entropy are read from the table of water saturation for saturated liquid.
- The water's output temperature, power of heat element and the input cold water's mass flow are displayed on the exchanger. The power of mixer is obtained by multiplication of the torque and the mixer's angular velocity which is specified on the exchanger (thus, the mixer power and speed are directly related)
- The rate of entropy generation is obtained using Eq. 22.

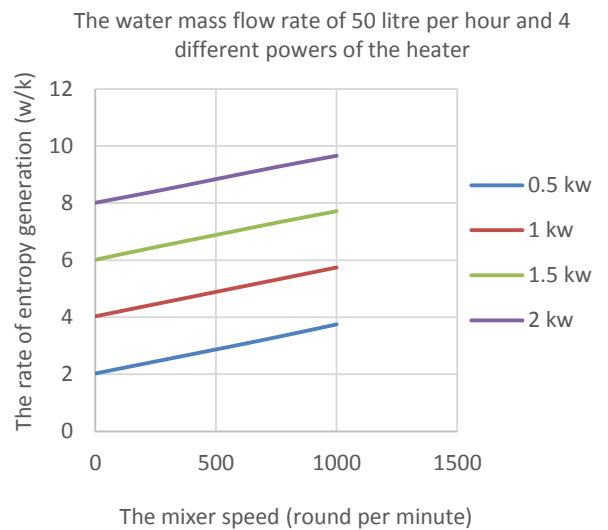


Figure 1. The rate of entropy generation according to the mixer speed for a fixed water mass flow rate of 50 liter per hour.

Fig. 1. shows the rate of entropy generation according to the mixer speed for the water mass flow rate of 50 liter per hour. Results indicate that along with the increase of mixer speed (over 0-1000 round per minute) and the heater power in four different values (0.5, 1, 1.5 & 2) kilo watt (kw), the rate of entropy generation according to watt per Kelvin (w/k) has been linearly increased. It is thus concluded that the less the heater power and mixer speed, the less the entropy generation.

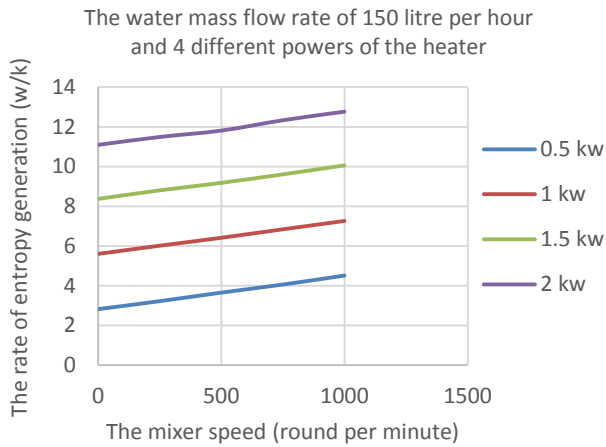


Figure 2. The rate of entropy generation according to the mixer speed for a fixed water mass flow rate of 150 liter per hour.

Fig. 2 shows the rate of entropy generation according to the mixer speed for the water mass flow rate of 150 liter per hour. Results indicate that along with the increase of mixer speed (over 0-1000 round per minute) and the heater power in four different values (0.5, 1, 1.5 & 2) kilo watt (kw), the entropy generation according to watt per Kelvin (w/k) has been linearly increased. It is thus concluded that the less the heater power and mixer speed, the less the entropy generation.

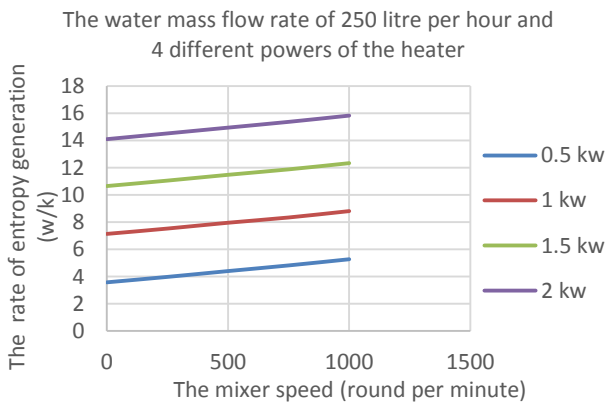


Figure 3. The rate of entropy generation according to the mixer speed for a fixed water mass flow rate of 150 liter per hour.

Fig. 3 shows the rate of entropy generation according to the mixer speed for the water mass flow rate of 250 liter per hour. Results indicate that along with the increase of mixer speed (over 0-1000 round per minute) and the heater power in four different values (0.5, 1, 1.5 & 2) kilo watt (kw), the entropy generation according to watt per Kelvin (w/k) has been linearly increased. By comparing the three diagrams (1), (2) & (3) it is thus concluded that the less the heater power, mixer speed and cold water mass flow rate, the less the entropy generation.

V. RESULTS

- No one denies the value of heat exchangers and their widespread application. Heat exchanger tank is one of these elements. By using the laws of mass conservation (continuity equation), energy conservation (the first law) and entropy balance (the second law), the present study attempted to obtain a relation for the entropy generation of heat exchanger tank. The obtained relation was then compared with the experimental results and evaluated.
- Considering the Eq. (22), the three parameters (the input cold water mass flow rate, power of heat element and mixer speed) influence the rate of entropy generation. Thus, these parameters are the performance evaluation criterion of the exchanger tank. Meaning that along with the increase of any of the aforementioned parameters, the rate of entropy generation for the heat exchanger tank would increase. In addition, it is decreased with their decrease. The results, predictable from the analysis of second law of thermodynamics for the heat exchanger tank, were confirmed by the experimental data and laboratory results. Moreover, the results of all three diagrams indicate that along with the increase of any of three parameters (the input cold water mass flow rate, power of heat element and mixer power or speed), the rate of entropy generation would increase which proves the compatibility of analytical and experimental relations.
- Therefore, for the optimal performance of a heat exchanger (according to the second law of thermodynamics), the result of which is an increase in the system's efficiency and productivity, a decrease in the energy consumption, system's loss, and finally environmental pollution, it is suggested to control the three parameters (the input cold water mass flow rate, heat element power and mixer speed) in their possible minimum levels.
- According to the values of entropy generation shown in diagrams, the optimized range for the cold water mass flow rate was 50-150 litre per hour, for the heater power was 0.5-1 kw and for the mixer speed was 0-250 rpm. The entropy generation rate has been it its lowest level in these ranges; meaning that the system has been performing in optimized conditions according to the analysis of second law of thermodynamics.

REFERENCES

- [1] Bejan, A., 1982, "Second-law analysis in heat transfer and thermal design", *Adv. Heat Transfer*, NO. 15.
- [2] Bejan, A., 1982, "Entropy Generation through Heat and Fluid Flow", Wiley, New York.
- [3] Bejan, A., 1995, "Entropy Generation Minimization", CRC Press, New York.
- [4] yilmaz, M. , sara , O. and karsli, S., 2001, "performance evaluation criteria for heat exchangers based on second law analysis", Ataturk university, Turkey.
- [5] Arif Hepbasli, 2006, A key review on exergetic analysis and assessment of renewable energy resources for a sustainable future, Department of Mechanical Engineering, Faculty of Engineering, Ege University, TR-35100 Bornova, Izmir, Turkey.
- [6] gong, M. and wall, g., 1997, "on exergetics economics and optimization of technical processes to meet environmental conditions", Chinese and American society engineers.
- [7] naphon, P., 2006, "second law analysis on the heat transfer of the horizontal concentric tube heat exchangers ", Thailand.
- [8] ozcelik, Y., 2007, "exergetic optimization of shell and tube heat exchangers using a genetic based algorithm, Ege university", Turkey.
- [9] paniagua, I. and martin, J. , 2013, "A new simple method for estimating exergy destruction in heat exchangers", university politecnica de Madrid.
- [10] Kakac, S. and Liu, H., 1997, "Heat Exchangers Selection Rating, and Thermal Design, CRC Press", New York.
- [11] shukuya, M. , and hammeche, a., 2002, "introduction of the concept of exergy", Yokohama .
- [12] Zhu. X. Feng.X., 1997, Combined Pinch And Exergy Analysis For Process Modification, *Applied Thermal Engineering*, vol 17, pp 249-261.