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Experimental performance investigation of a shell and tube heat exchanger by exergy based sensitivity analysis

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Abstract Heat exchangers are used extensively in many industrial branches, primarily so in chemical and energy sectors. They also have important household usage as they are used in central and local heating systems. Any betterment on heat exchangers will serve greatly in preserving our already dwindling and costly energy resources. Strong approach of exergy analysis -which helps find out where the first steps should be taken in determining sources of inefficiencies and how to remedy them- will be used as a means to this end. The maximum useful work that can be harnessed from systems relationships with its environment is defined as exergy. In this study, the inlet and outlet flow rate values of fluids and temperature of hot stream both on shell and tube parts of a shell-tube heat exchange system have been inspected and their effects on the exergy efficiency of this thermal system have been analyzed. It is seen that the combination of high tube side inlet temperature, low shell side flow rate and high tube side flow rate are found to be the optimum for this experimental system with reaching 75, 65, and 32 % efficiencies respectively. Selecting operating conditions suitable to this behavior will help to increase the overall efficiency of shell-tube heat exchange systems and cause an increment in energy conservation.

List of symbols

Ex	Exergy (kW)
G	Gibbs free energy (kJ/kg)
H	Enthalpy (kJ/kg)
S	Entropy (kJ/kg K)
T	Temperature (K, °C)
P	Pressure (bar, atm)
c	Specific heat (kJ/kg K)
v_m	Volume (L, m^3)
x	Composition (−)
ν	Stoichiometric constant (−)
Q	Heat (kW)

1 Introduction

The heat exchangers which have the primary function of transferring heat between different fluids with different temperatures are commonly encountered in almost all branches of engineering. Heat exchangers are used in volumetric heating, power production facilities, food industry, in recovery of excess heat, air conditioning and cooling facilities, chemical processes, in cars and ships, in aviation and spacecraft and in cooling of electronic devices.

In simple terms, a heat transfer takes place inside a heat-exchanger, between two different currents of liquid and/or gas with different inherent temperatures, by means of a variety of utilities, resulting in heating or cooling of processed current.

The exergy analysis method used in this study is based on the second law of thermodynamics [1, 2]. This law takes into consideration the quality of energy as well as the quantity of it, thus it can be used to figure out the real work-related value of a given matter, which in turn helps finding out inefficiencies, energy losses and thermodynamic inadequacies of a process or a system [3].

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Dwindling energy sources and the energy shortage forced scientists and engineers looking for new approaches and methods in thermal engineering, and in parallel, thermodynamics. Most common of these new approaches are thermodynamic analysis, reduction of entropy and exergy analysis, all of which are widely used. Amongst these, exergy analysis helps to find out the source and amount of energy losses in a system and the cost of these losses to the system as a whole.

Any betterment on heat exchangers which have such a prominent usage will serve greatly in preserving the energy which is becoming ever more sparse and costly [4]. Furthermore, improvements in energy usage have secondary effects on our environment such as reducing the greenhouse gas emission [5].

Heat exchangers are deeply studied in the literature from design and performance points of views. There are various studies that investigates the performance of the heat exchanger systems in an exergetic point of view [6–10]. Moreover various studies considered optimization studies for revealing the performance of the heat exchangers from different parameters like tube diameters, flow rates and temperature scales by single and multi-objective optimization algorithms [11–15]. Studies based on genetic algorithm are focused on optimizing the heat exchangers in a multi-objective manner, considering a large Pareto set of solutions that keep trade off in the table. Capital cost, operating cost and system efficiency are conflicting parameters for heat exchangers in general [16]. It is figured out that there is a large room for energy efficiency increment [14] and cost decrease in the heat exchangers by operating at optimum parameters that is found as a result of computer aided optimization studies. Experimental studies for covering new design strategies for reaching exergy efficiency increments are conducted in the literature and found that overall heat transfer coefficient can be increased up to 19.7 % that results a 14.1 % of exergetic performance increment [9]. Second law and entropy generation analysis are also a topic of the researcher for revealing the inefficiencies in heat exchangers [17–19]. Some studies focused on analytical investigation of heat exchangers in an dynamic structure with a feed-forward control heuristic [20]. An exergetic analysis conducted for investigating various nanofluids in an helically coiled heat exchanger considering parameters of particle volume concentration, heat exchanger duty parameter, coil to tube diameter ratio and Dean number [21].

The aim of this study is to make a detailed experimental analysis covering a parametrical data gathering on shell-tube type heat exchangers and carry out an exergy based analysis of the heat exchange system in order to reveal its true exergy efficiency. The parameters to be inspected are the temperature and flow rate of inlet and outlet fluids in both shell and tube sides of a shell-tube heat exchanger. By this sensitivity analysis an optimum operating parameter set is to be proposed for this system and the importance of the exergy and sensitivity analysis on operating thermal systems are underlined by determining exergetic efficiencies. By introducing an exergy based parametrical sensitivity analysis and experimental optimization for a shell and tube heat exchanger system this study brings a different perspective to the literature.

2 Exergy analysis

Exergy defines the maximum amount of work that can be harnessed from a given energy source [2]. Thus, total exergy of a system is determined by involving all the different potential sources within. If special types of energy like nuclear, magnetic, electric and surface tension are ignored, total exergy of a system (Ex) is made up of, physical exergy ($\mathrm{Ex_{ph}}$), kinetic exergy ($\mathrm{Ex_{ke}}$), potential exergy ($\mathrm{Ex_{pe}}$) and chemcial exergy ($\mathrm{Ex_{ch}}$) [1, 22]. Total exergy;

$$\mathrm{Ex} = \mathrm{Ex_{ph}} + \mathrm{Ex_{ke}} + \mathrm{Ex_{pe}} + \mathrm{Ex_{ch}} \tag{1}$$

In the heat exchangers inspected as the scope of this study, kinetic and potential energy changes are small enough to be ignored and also no chemical reactions take place within them. Thus, total exergy of shell-tube heat exchangers is just made up of physical energy [23].

$$\mathrm{Ex_{ph}} = \mathrm{H} - \mathrm{H_0} - \mathrm{T_0}(\mathrm{S} - \mathrm{S_0}) \tag{2}$$

A flows physical energy is expressed as a function of two components, in order to make the analysis of a thermodynamic system more convenient.

$$\mathrm{Ex_{ph}} = \mathrm{Ex}^{\Delta \mathrm{T}} + \mathrm{Ex}^{\Delta \mathrm{P}} \tag{3}$$

The exergy that is caused by the type of the flow and the difference between the temperature between the flow and its environment is called the thermal component ($\mathrm{ex}^{\Delta \mathrm{T}}$), the exergy caused by pressure difference is called pressure component ($\mathrm{ex}^{\Delta \mathrm{P}}$)

$$\mathrm{Ex_{ph}} = \mathrm{c}[(\mathrm{T}-\mathrm{T_0}) - \mathrm{T_0} \ln \mathrm{T}/\mathrm{T_0}] - v_{\mathrm{m}}(\mathrm{P} - \mathrm{P_0}) \tag{4}$$

Physical exergy can also be calculated from enthalpy and entropy change in the thermal systems as noted;

$$Ex_{ph} = (E - U_0) + P_0(V - V_0) - T_0(S - S_0) \tag{5}$$

$$Ex_{ph} = (H - H_0) - T_0(S - S_0) \tag{6}$$

For systems that include chemical reaction chemical exergies of the materials must be kept into account. Chemical exergy is the departure of the components amount and type from those present in the selected reference environment. So the energy derived from the chemical reaction through reaching equilibrium with the reference compositions are called as chemical exergy.

$$Ex_{ch} = RT_0 \ln\left(\frac{P}{P_0}\right) \tag{7}$$

$$E_{ch} = \Delta G - \sum_j v_j E_{0,ch,j} \tag{8}$$

$$E_{ch} = E_{0,ch,j} + \sum_j x(\ln(x)) \tag{9}$$

Based on the current studies in literature, how the exergy analysis method could be used in systems working on a thermal function could be summarized as follows [24]:

- Determining the real amounts of losses of a given thermal system. Helps finding out thermodynamic defects of a system in a quantitative fashion.
- Determining the energy quality of a system from a thermodynamics perspective. Helps comparison between systems with equal efficiency.
- To remedy the inefficiencies in the system being worked on by helping to find their sources.
- Helps in situations where the first law of thermodynamics falls short in finding the losses and their potential sources in a system.
- As it makes easier to calculate the real value of energy and to make evaluations, helps in preliminary design of processes and systems, feasibility calculations and design optimizations.

3 Sensitivity analysis

Sensitivity analysis investigates the uncertainty in a mathematical model or a system. The sources of this uncertainty may be various depending on the effecting parameters [25]. This method is used for investigating the robustness of the system, reducing the uncertainties and enhancing the information on the operating conditions and system relation [26].

Sensitivity analysis allows engineers and designer to overcome the effect of various parameters in the design or pilot stage of a project and lets them to control the system better in normal operating stage.

The basic aim of the analysis is to investigate whether the system or model is sensitive to small changes in one or more operating parameter. Determining the magnitude of this effect is also in the scope of this method.

4 Experimental setup and methodology

In this study, a shell-tube heat exchanger's working parameters, which are temperatures and flow rates of input and output fluids of shell and tube sides, have been inspected (Table 1). Shell side of the exchanger is connected to the tap water and tube side is connected to the heated tank. Experimental apparatus is a set up as seen in Figs. 1 and 2. System can digitally measures and record temperature and flow rate values for both shell and tube side.

In this study, shell and tube side input flow rates and tube side inlet temperature are taken as operating parameters and data have been gathered from each of the parameter's perspectives. The values of these operating parameters and their base case conditions have been presented in Table 1.

Table 1 Ranges of investigated operating parameters

Set number	Investigated parameters	Investigation range	Base case value
1	Shell side input flow rate (L\m)	1.5–5.0	3
2	Tube side inlet temp. (°C)	20–55	35
3	Tube side input flow rate (L\m)	0.8–4.8	2.4

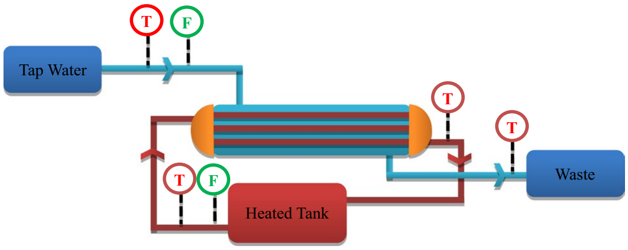

Fig. 1 Scheme shell-tube type heat exchanger experimental setup

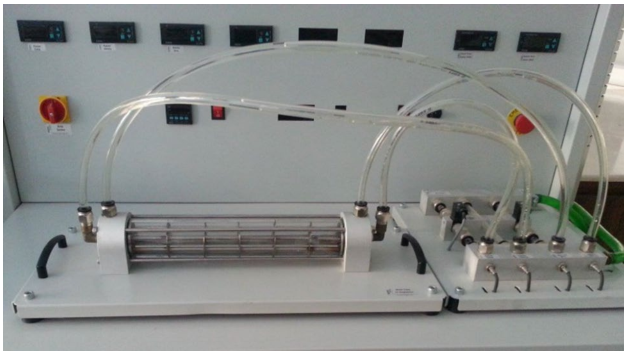

Fig. 2 Experimental shell and tube heat exchanger system

The operating parameters other than the investigated one are kept constant in base case values in experiments. During the study, reference environmental temperature have been measured as 20 °C and assumed to be constant in all experiments.

The values of outlet temperatures of shell and tube sides of the heat exchanger system are recorded as experimental data as well as the operating parameters. The total uncertainty for heat exchange system is calculated as 0.707 including flow and temperature measurements (Table 2). The values are recorded by the operator after the system reaches steady state which is assumed as the parameters being constant for 2 min. The sets are repeated 3 times for avoiding operational and other errors.

Table 2 Sensitivities of the experimental apparatus

Measurement	Instrument	% Sensitivity
Shell side input flow rate (L\m)	Digital flowmeter	±0.1
Tube side input flow rate (L\m)	Digital flowmeter	±0.2
Tube side inlet temp. (°C)	Digital thermometer	±0.1
Tube side outlet temp. (°C)	Digital thermometer	±0.1
Shell side inlet temp. (°C)	Digital thermometer	±0.3
Shell side outlet temp. (°C)	Digital thermometer	±0.3

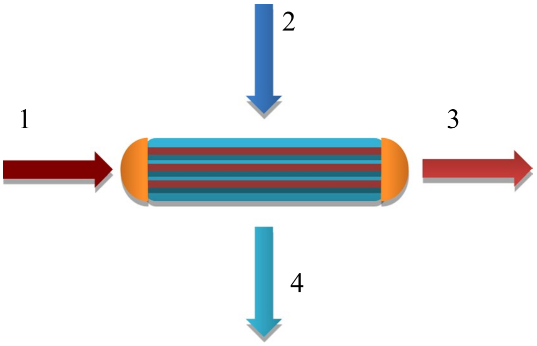

Fig. 3 Exergy analysis of a heat exchanger

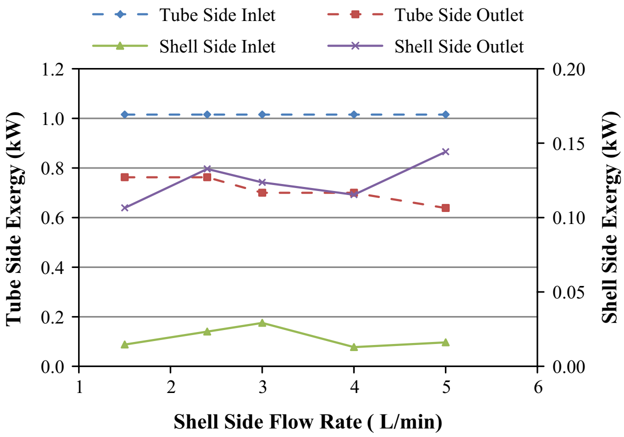

Fig. 4 Exergy values with respect to shell side flow rate

5 Exergy analysis of shell and tube heat exchanger system

The experimental setup which is used for investigation of the heat transfer performance is developed in order to decrease the temperature of the hot water inlet to the tube side of the heat exchanger. On the other hand the tap water is used as the coolant medium for this operation to simulate a heat exchange system.

The governing exergy analysis equation is presented below and necessary exergy values for the calculation are obtained depending on the results of the experimental analysis (Fig. 3).

$$\dot{I}_{hex} = \dot{E}x_1 + \dot{E}x_2 - \dot{E}x_3 - \dot{E}x_4 - \dot{Q}_{hex} \tag{10}$$

The most important parameter for a thermal system like heat exchangers is the exergy efficiency when the system capabilities versus the system boundaries are taken into account. In this study the exergy efficiency value is defined as the difference between the exergies of shell-side at inlet and outlet to the difference of exergies of tube-side at the inlet and outlet in accordance with the aim of the study to reveal the heat transfer properties of the system.

$$\eta_{sys,exergy} = \frac{\dot{E}x_4 - \dot{E}x_2}{\dot{E}x_1 - \dot{E}x_3} \tag{11}$$

6 Results

As a result of a series of tests made in three sets, exergy efficiency and exergy values have been calculated by means of exergy analysis. The temperature profile has also been introduced in this section.

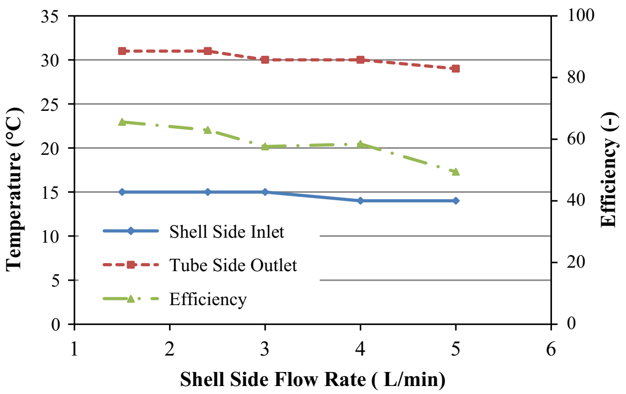

Fig. 5 Temperature and efficiency values with respect to shell side flow rate

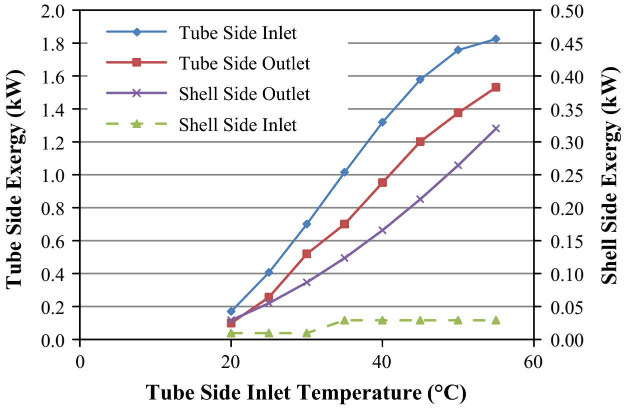

Fig. 6 Exergy values with respect to tube side inlet temperature

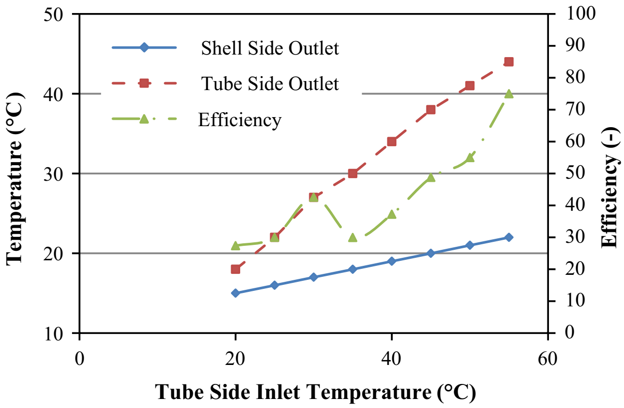

Fig. 7 Temperature and efficiency values with respect to tube side inlet temperature

The effect of shell side flow rate on the performance of the heat exchanger is investigated in SET-1, the other operating parameters like tube side inlet temperature and shell side temperature were kept constant. Measurements and calculations reveal that an increase in the flow rate of the cooling water decreases the efficiency by 15 % as it can be seen from Fig. 5 as well as increasing exergy values of shell side outlet in Fig. 4. This increase means a decrease in the heat transferred results in an efficiency loss. That leads us to consider the entropy increase in finite temperature differences as reversible heat transfer has also been achieved by small temperate differences.

As seen on Figs. 6 and 7, the effect of tube side inlet temperature is investigated in SET 2 and shown in Figs. 6 and 7. It is seen that with the increase of tube side temperature that is the hot flow in the heat exchanger system, the exergy efficiency increases by 40 % approximately. This behavior is expected and has positive impact on efficiency. Also the increase in the exergy values both in shell and tube sides can also be seen in the figures that leads an efficiency increment.

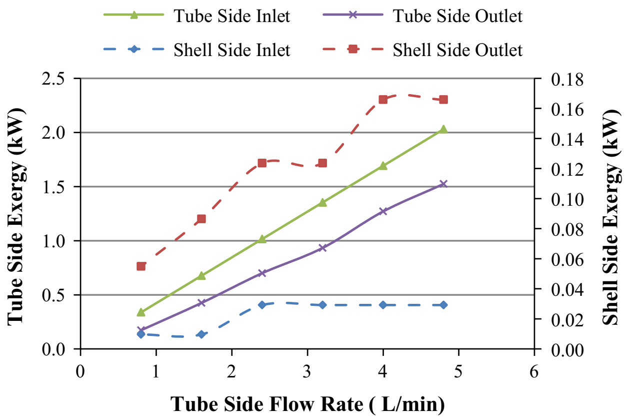

Fig. 8 Heater intake water flow rate values relation with exergy

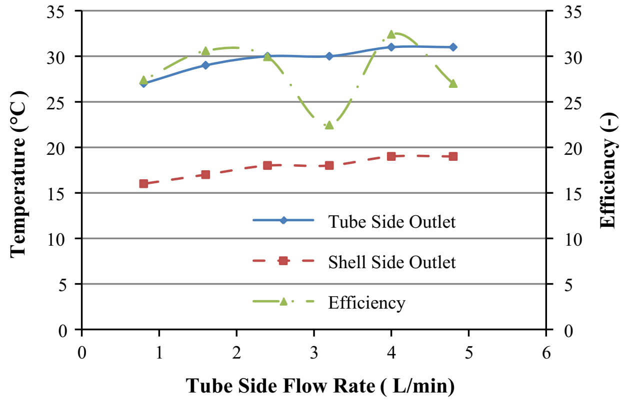

Fig. 9 Heater intake water flow rate values relation with efficiency

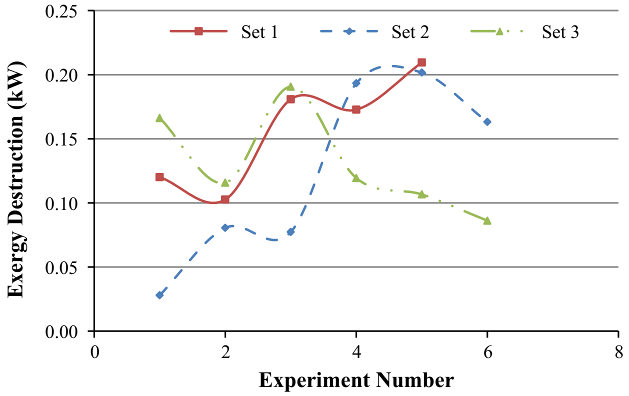

Fig. 10 Exergy destruction in experiments with respect to the set number

In Set-3, the effect of tube side flow rate is selected as the main parameter. The results of experiments are shown in Figs. 8 and 9. It is evident that as the tube side flow rate is decreased, tube side outlet temperature and shell side inlet and outlet temperatures are decrease. This is reflected on the exergy values depending on these as a decline as well; however efficiency values do not share the same tendency and instead see a fluctuating course. Highest efficiency value has been determined as 32 %. As seen on Fig. 9, efficiency stays between 20 and 35 %. This leads us to conclude tube side flow rate has a limited effect on the exergy efficiency of the heat exchanger system since the small cross-sectional area of the tubes results in high Reynolds numbers that increase the overall heat transfer coefficient.

Moreover the tendencies of the irreversibilities (exergy destruction) are also calculated and shown in Fig. 10. This investigation is based on for every set of experiment with the experiment number in order to reveal the behavior of the irreversibilities through the changing parameters. It is seen that the results are in accordance with the exergy efficiency values as the increase in efficiency is because of lower irreversibilities.

7 Conclusion

This study shows clearly that exergy analysis method is an important and strong approach in determining performance of the thermal systems. This idea is further emphasized as industrial scale heat exchangers are one of the primary sources of energy loss in application and exergy analysis is extremely convenient to analyze and determine the optimum working parameters.

With this study, exergy analysis on a shell and tube heat exchanger system has shown a clear connection between exergy efficiency values and primary working variables of the system. In three sets of tests, tube side inlet temperature, tube side inlet flow rate and shell side inlet flow rate have been parametrically inspected as the primary working variables.

As a result of these tests, it is determined that exergy efficiency increases as the temperature of the hot fluid inlet of the exchanger increases. Besides, increasing the inlet flow rate increases exergy however efficiency values stay unchanged. Also increasing the output flow rate, on the other hand, decreases the efficiency. The exergy destruction fluctuates between 0.05 and 0.2 kW regarding the operating conditions that negatively affects the exergetic efficiency.

By this sensitivity analysis it is seen that the efficiency of the system is greatly dependent on the ranges of temperature and flowrates. The efficiencies can change up to 40 % in a change in operating temperatures and that underlines to the importance of process control in operation of thermal systems as these systems must strictly operate at the design values. Hence the importance of the exergetic design perspective is also underlined by the results so designers should consider these analyses before design phase of a thermal system.

As a conclusion, the combination of high tube side inlet temperature, low shell side flow rate flowrate and high tube side flow rate is found to be the optimum for this experimental system. This is seen from the trends of the efficiency curves of each set by having efficiency of 75 % by 55 °C tube side inlet temperature, 65 % by 1.5 L/m shell side flow rate and 32 % by 4 L/m tube side flow rate. The considerable range of change in the efficiency of the test apparatus during the test points to a greater importance of exergy analysis in determining the optimum working conditions of industry scale heat exchangers and thermal systems, as well as their initial designs.

Future studies are planned to include exergoeconomic tests and analysis; furthermore, an optimization study run over a theoretical modeling of the system is also being considered as these studies should reveal the entire character of the thermal system.

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