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Experimental investigation of exergy destruction in a 8-kW power plant

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Abstract
In this study, the exergy destruction and irreversibility analysis of an 8 kW experimental power plant was presented. The first objective of the present study was to find the component with primary irreversibility or exergy destruction in the system. In addition, the effect of different operation conditions such as boiler pressure and output power on the irreversibility of components was investigated. Based on the results, it was found that boiler and feed water tank has the maximum and minimum irreversibility in the system, respectively. Then, the boiler as the primary exergy destruction component in the system was focused. The boiler was divided into three regions namely: combustion, heat transfer, exhaust and the irreversibility in each region was evaluated .The results showed that the maximum part of irreversibility belongs to the heat transfer region with about 54.8% followed by 39% and 6% for combustion and exhaust regions, respectively.

Keywords: Experimental power plant, Exergy destruction, Irreversibility.

1. Introduction

Analysis of power generation systems is necessary for the efficient use of energy resources. The first law of thermodynamics is the most common method for energy analysis of systems, but the combined utilization of the first and second law of thermodynamics or exergy analysis provides the tool distinction between energy losses and irreversibilities in the process. By using exergy analysis, any process and component in the system that having the largest exergy destruction can be identified and this in turn helps the designers to improve the system performance.

The exergy concept in power generating plants was interested by a number of researchers. For instance, Habib et al. [1] conducted a research on the thermodynamic performance analysis of the Ghazlan power plant in Saudi Arabia. The system was studied based on the first and second law of thermodynamics according to the available data. A full exergy analysis was carried out to identify the component that has the largest exergy destruction in the whole system. The irreversibility of different components was compared as a function of load. They revealed that major exergy destruction or irreversibility occurs in the boiler. They also revealed that first law results were misleading and evaluation should be based on the second law of thermodynamic results.

In another research, exergy of a cryogenic hydrogen fuel power plant was studied by Fiaschi and Manfrida [2]. The system was studied by exergy balance approach. The system was studied to check which component is responsible for the largest irreversibility.

The performance of a conventional power plants (Rankine steam cycle) was analyzed based on the exergy concept by Verkhivker and Kosoy [3]. Based on this study, the main irreversibilities were associated with the chemical transformation of exergy into heat, the subsequent transfer of this heat to the working fluid and the heat exchange of the net heaters. In another research, Kwak et al. [4] studied a 500 MW combined cycle plant in exergetic and thermo-economic point of view. The quantitative balance of the exergy and exergetic cost for each component and for the whole system was considered in the investigation. A computer program was developed to determine the production costs of power plants, such as gas and steam plants and gas turbines cogeneration plants. It was found that if correct information costs for every component can be supplied, the unit cost of products can be evaluated.

A 300 MW pulverized coal fired power plant located in Yiyang (China) was studied by Zhang et al. [5]. A cost analysis method based on thermodynamics on the power plant was investigated. The cost formation of the power plant and the effect of different operating conditions and parameters on the performance of each component were analyzed. A simulator was developed based on the thermodynamic model of the power plant for this purpose. By using the simulator, the exergy cost was studied, and it was found that the specific irreversibility cost was more suitable than the unit exergy cost of a product in quantifying and representing the production performance of a component. Performance and parametric investigation of a binary geothermal power plant by exergy approach were investigated by Kanoglu and Bolatturk [6]. Actual plant data were used to determine the plant performance and find the sites with primary exergy destruction. It was shown that brine reinjection, heat exchanger and condenser losses had the greater exergy destruction. In this study, the effect of parameters such as turbine inlet pressure and temperature and the condenser pressure on the exergy and energy efficiencies, the net power output and the turbine reinjection temperature were also investigated.

Aljundi [7] investigated the energy and exergy concept in a steam power plant in Jordan. The system components were analyzed separately to identify and quantify the sites having the largest energy and exergy losses. The effect of varying the reference environmental temperature was also studied. It was found that the percentage ratio of the exergy destruction to the total exergy destruction was maximum in the boiler system (about 77%) followed by the turbine (about 13%) and the forced draft fan condenser (9%), respectively.

Since varying the operating conditions in a real power plant to study the effect of different operating conditions on the irreversibility of components is almost impossible. Therefore, a simulated 8 kW power plant working in the Rankine cycle was used to this purpose. The primary components of exergy destruction were identified and the effect of varying operating conditions such as boiler pressure and output work was investigated in this research.

2. Theory relevant to the present research

2.1 Stream exergy

In a control volume, we call an exergy accompanied with a flow that inters a control volume, stream exergy. So, the stream exergy of a fluid is the maximum work that can be obtained from it when it undergoes a reversible and steady process from its initial state to the atmosphere state and during this process, there is heat transfer only with surrounding atmosphere [8].

By assuming the second state as a dead state we will have:

$$w_{rev,u} = (h_0 - T_0 s_0) - (h + \frac{v^2}{2} + gz - T_0 s) \tag{1}$$

where $w_{rev,u}$ is the reversible, useful work (W), h is the specific enthalpy (Kj/kg), T is the temperature (k), s is the specific entropy ($Kj/kg.k$), v is the velocity (m/s), g is the gravitational force, z is the height (m) and 0 indicates the dead state.

According to the fact that the work taken from equation (1) is negative and exergy is positive, so stream exergy in per mass will be in the following form [8]:

$$\psi = \left(h + \frac{v^2}{2} + gz - T_0 s \right) - (h_0 - T_0 s_0) \tag{2}$$

where ψ is the stream exergy (Kj/kg).
And it can be rewritten in the form:

$$\psi = (h - h_0) - T_0(s - s_0) + \frac{v^2}{2} + gz \tag{3}$$

So, the stream exergy difference between the inlet flow (index1) and exit flow (index2) can be expressed by:

$$\begin{aligned}\psi_2 - \psi_1 &= (h_2 - h_1) - T_0(s_2 - s_1) \\ &+ (ke_2 - ke_1) + (pe_2 - pe_1)\end{aligned} \tag{4}$$

where Ke is the kinematic energy (W) and Pe is the potential energy (W).

2.2 Exergy balance for a control volume

The exergy balance for any control volume in a steady state condition with negligible potential and kinetic energy changes can be expressed by:

$$\dot{I}_{total} = \sum_{in} \dot{m}b - \sum_{out} \dot{m}b \tag{5}$$

where, $\dot{I}_{total}$ is the total irreversibility (kW) and $\dot{m}$ is the mass flow rate (kg/s).
b can be found using the following equation.

$$b = h + ke + pe - T_0 s \tag{6}$$

3. Experimental power plant set-up

The experimental power plant that works in Rankine cycle was consisted of a fire tube boiler with 14 tubes. The maximum operational pressure was 11 bar and its thermal surface and super heat surface was $8\,m^2$ and $0.6\,m^2$, respectively. The burner's fuel was liquid diesel fuel and the turbine was an impulse type with maximum output of 8 kW in 3000 RPM. The experimental power plant and its schematic diagram have been illustrated in Figures 1 and 2. The maximum excitation current and excitation voltage of the generator was 0.3 Amp and 21 Volt, respectively. The maximum current and voltage produced was 23 Amp and 215 Volt.

Figure 1. Experimental power plant

4. Experimental parameters

In this study, experiments were carried out in the boiler pressure of 5 to 8 bar producing 3 output power for every operating pressure. The measurements were performed when the system reached the steady state condition. The exergy destruction was determined by considering every component as a control volume and applying equation (5) for that specific component. Thus, for this series of experiments, tests were performed as follows:

- Boiler pressure: 5 bar, 6 bar, 7 bar and 8 bar.
- Output work: 1.2 kW, 2.6 kW and 4.1 kW.

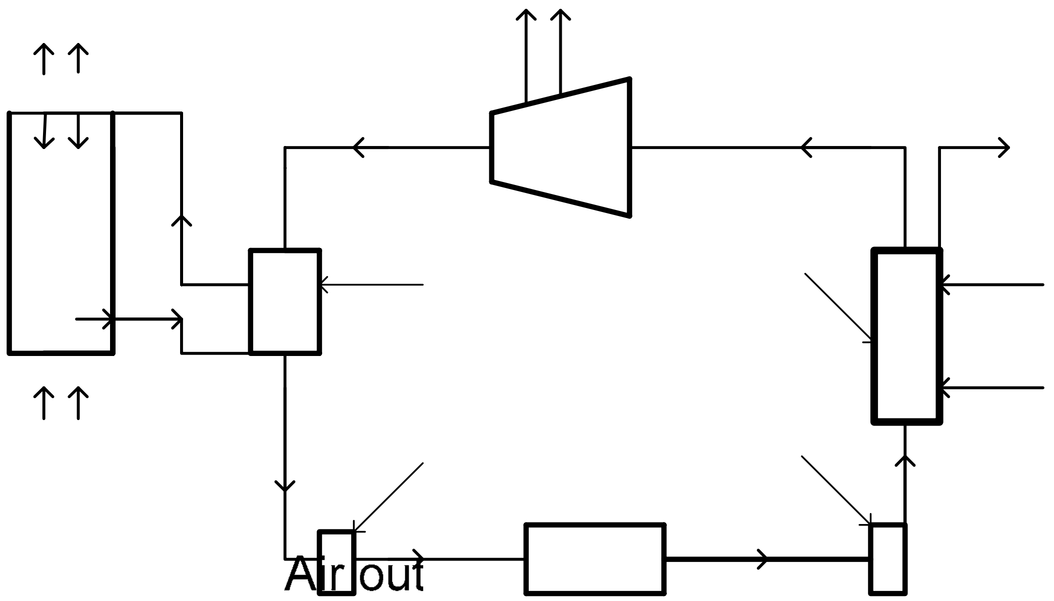

Figure 2. Schematic diagram of the experimental power plant

5. Results and discussion

The irreversibility of components at two representative boiler pressures has been shown in Figures 3 and 4. The results showed that the boiler irreversibility was the maximum amount in the boiler pressure range of study. According to the experimental results, the amount of irreversibility increased as the output work increased. Based on the experimental results, the irreversibility of components including boiler, turbine, condenser, and feed water tank increased with the increasing of the output work.

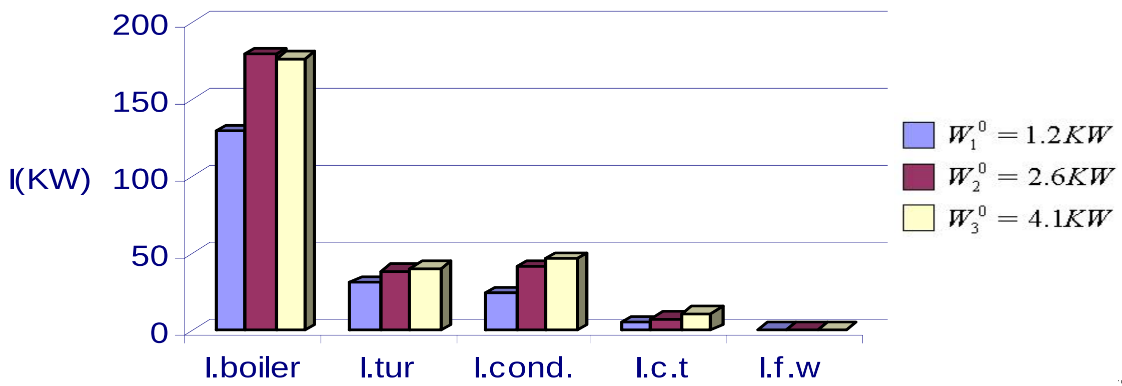

Figure 3. Irreversibility of components at the boiler pressure of 5 bar

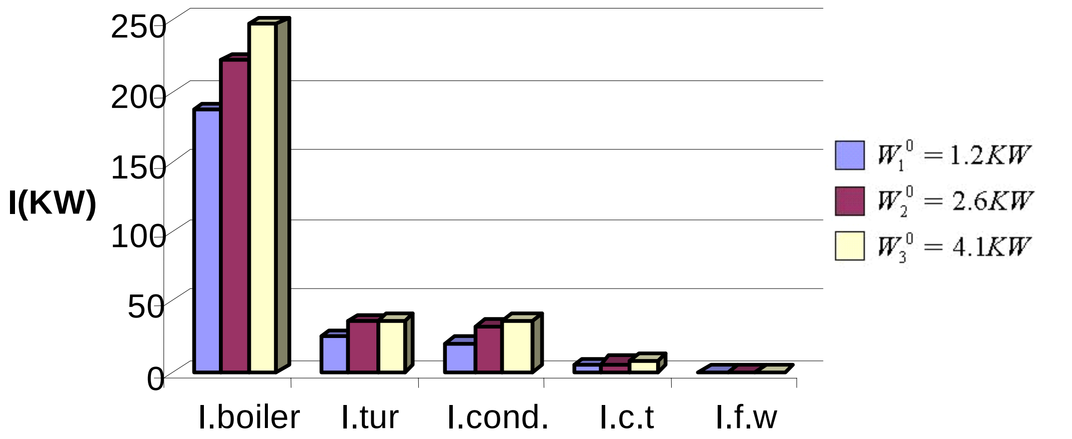

Figure 4. Irreversibility of components at the boiler pressure of 8 bar

The percentage ratio of the irreversibility in the components to the total irreversibility has been shown in Figures 5 and 6. The results showed that the percentage ratio of boiler irreversibility has a reducing trend as the output work increased.

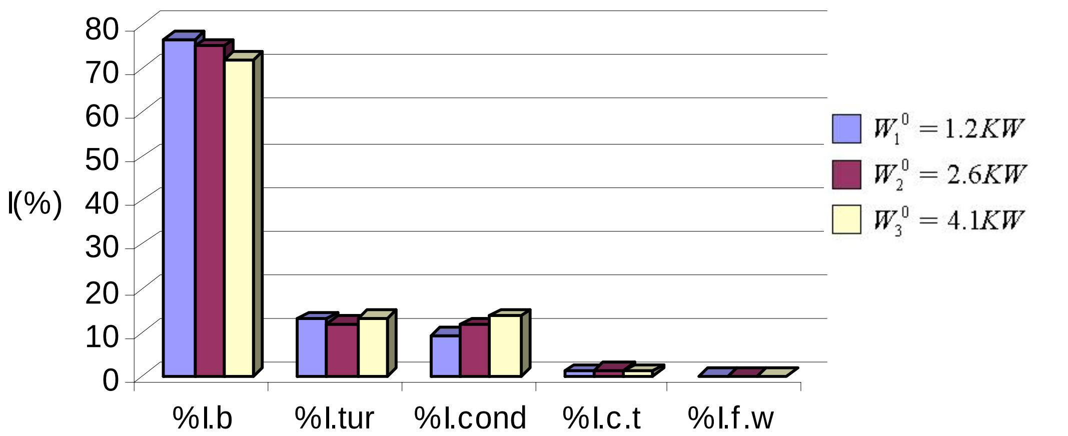

Figure 5. Percentage ratio of irreversibility in components at the boiler pressure of 7 bar

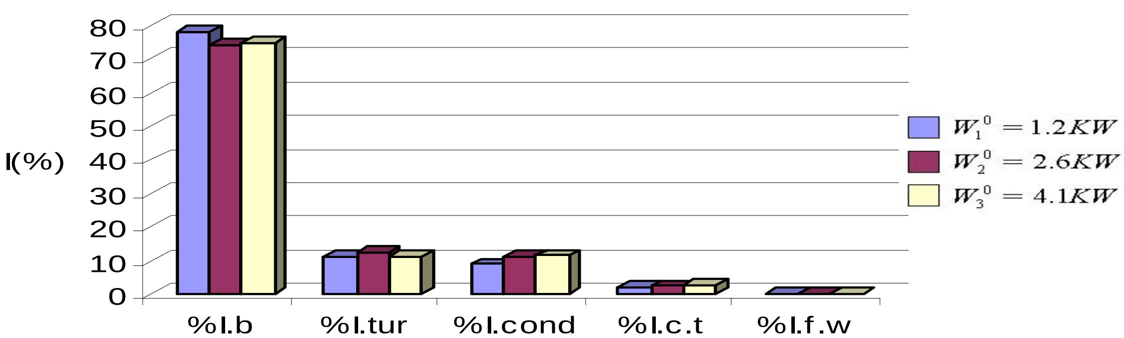

Figure 6. Percentage ratio of irreversibility in components at the boiler pressure of 8 bar

After determining the irreversibility of components, the boiler which has the highest exergy destruction in the system was focused. The boiler was divided into 3 regions namely: combustion, heat transfer and exhaust as shown in Figure 7.

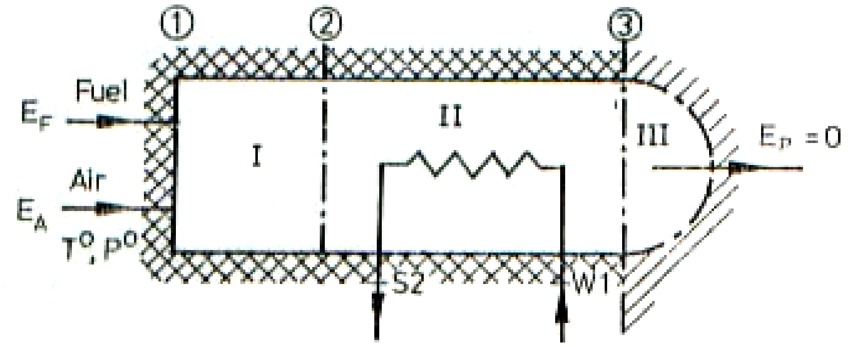

Figure 7. The boiler regions (I: combustion, II: heat transfer, III: exhaust)

According to the results, it was found that the maximum portion belongs to the region 2 or heat transfer region followed by the combustion and exhaust regions. The high exergy destruction in the heat transfer area is mainly because of heat transfer and temperature difference between two hot and cold resources. For instance, at the boiler pressure of 6 bar and output work of 1.2 kW, the percentage ratio of irreversibility in the heat transfer region (%I.R.2) was about 53% and for the combustion region (%I.R.1) and exhaust region (%I.R.3) were about 41% and 6%, respectively as illustrated in Figure 8.

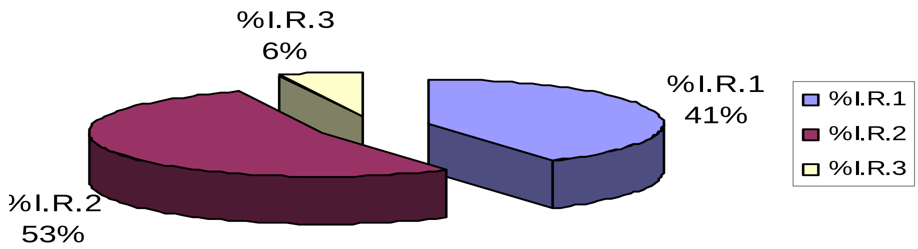

Figure 8. Percentage ratio of irreversibility in the boiler regions at the boiler pressure of 6 bar and output work of 1.2 kW

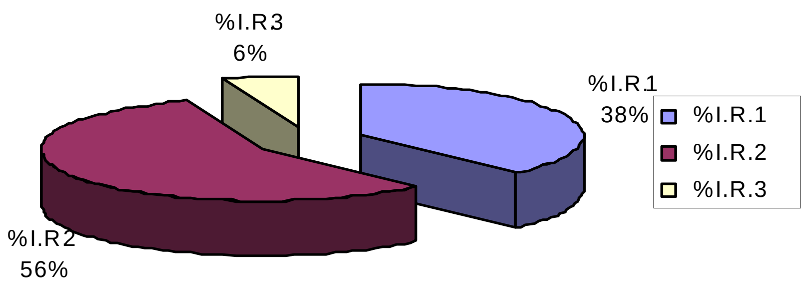

Figure 9. Percentage ratio of irreversibility in the boiler regions at the boiler pressure of 8 bar and output work of 1.2 kW

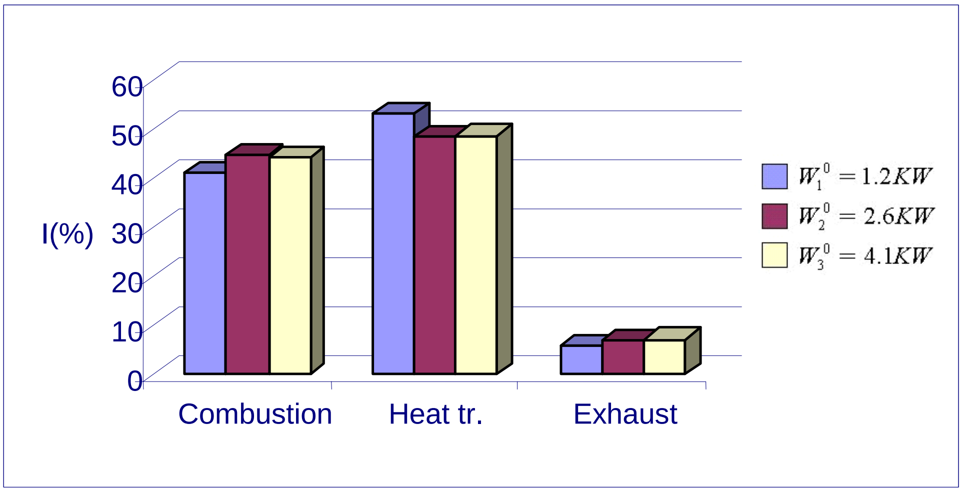

Figure 10. Percentage ratio of irreversibility in the boiler regions at the boiler pressure of 6 bar and different output works

Also in Figure 9, the percentage ratio of irreversibility in the boiler regions has been illustrated at the boiler pressure of 8 bar and output work of 1.2 kW.

Figure 10 shows the effect of output work on the percentage of irreversibility in the boiler regions. As it can be seen from Figure 10, the percentage ratio of irreversibility in the heat transfer region was the maximum one. Moreover, the portion of irreversibility in the heat transfer region decreased with the increasing of the output work. But, the percentage of irreversibility in the combustion region has an increasing trend. The portion of irreversibility in the exhaust region is the minimum and its change was little.

6. Conclusion

In this research, the exergy destruction as well as the effect of some different operation conditions such as the boiler operation pressure and output power on the exergy destruction of components has been presented.

By doing the series of experiments, it was found that the boiler was the primary exergy destruction component in the system with about 70% followed by condenser and turbine. Moreover, it was shown that the portion (percentage ratio) of boiler irreversibility was decreased as the output power was increased. Furthermore, the boiler regions were analyzed to find the region with the highest portion of irreversibility. After the determination of exergy destruction in the boiler regions, it was found that the heat transfer region has the highest portion with about 50% followed by the combustion and exhaust regions. The effect of studied parameters also showed that, by increasing the output power in a fixed boiler pressure, the portion of irreversibility in the first and third regions (combustion and exhaust) has an increasing trend.

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