Middle-East Journal of Scientific Research 9 (2): 253-256, 2011
ISSN 1990-9233

Optimization and Exergy Analysis for Advanced Steam Turbine Cycle

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Abstract: This paper intends to investigate the optimization of Rankine cycle using exergy analysis methods. The results of steam power plant optimization for open feed water heaters through writing computer code has been offered and is compared with Haywood's[1] analytic results as well as Habib'sand his colleagues' [2] results for close feed water heaters. It will be demonstrated that the application of open feed water heaters, in comparison to the result mentioned above, provides optimal situation and leads to more efficiency. Also, in close heater position, it is observed that for some of the amounts the relative efficiency is negative, but in open heater position, the amounts will remain positive all the time.

Key words: Optimization · Exergy · Advanced steam turbine cycle

INTRODUCTION

Exergy analysis is applied as a strong tool for analyzing energy systems and power producing machines. In this method, the efficiency of different sources of energy and the factors reducing this efficiency is investigated completely and precisely [3].

Using exergy method, we can obtain precise measurement for loses of a cycle and their actual deficiency and their right position. This can be used for all of the systems where simple or complex. Exergy analysis method also gives precise measurement of the efficiency of system for complex compound systems and open systems.

Notwithstanding the processes of a cycle affect each other and one's loses may affect other parts; the advantage of exergy method is its ability to predict the amount of effect of any part on other parts of system and specify the relation between loses [4].

Exergy Analysis: The relationship of steam turbine cycle equilibrium, together with energy diagram is demonstrated in Fig. 1. The shaded parts represent exergy losses. Demonstrating exergy equilibrium as a graph, in systems, is a usual and useful method in exergy analysis of systems and thermodynamics. A quite impressive demonstration of this is given in Fig. 1. [5].

Considering Fig.1 the exergy equilibrium relationship for boiler, turbine and condenser is as follows [3]:

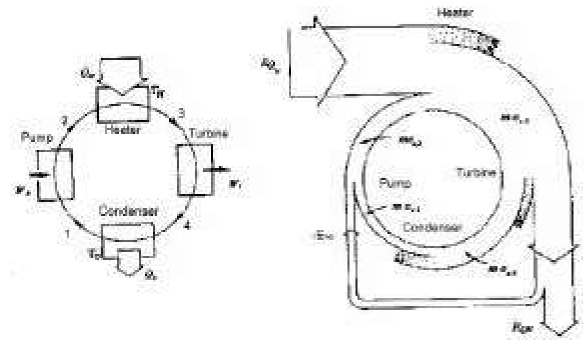

Fig. 1: Exergy losses in Rankine cycle and energy diagram

$$\text{Boiler: } \dot{m} e_{x,3} = \dot{E}_{Qo} + \dot{m} e_{x,2} - T_0 \dot{s}_{gen,boiler} \quad (1)$$

$$\text{Turbine: } \dot{E}_{W_t} = \dot{W}_t = \dot{m} e_{x,3} - \dot{m} e_{x,4} - T_0 \dot{s}_{gen,turbine} \quad (2)$$

$$\text{Condenser: } \dot{m} e_{x,1} = \dot{m} e_{x,4} - T_0 \dot{s}_{gen,condenser} \quad (3)$$

Regenerative Cycle with Open Feedwater Heaters: Fig(2) shows a regenerative cycle with *n* open feed water heater [6].

Feed water is heated step by step and by injected steam through turbine phases. Following each heater there is a pump that is responsible to make the feed water pressure reach injected steam pressure in next heater. Irreversibility due to feed water heater's application has two reasons [6]:

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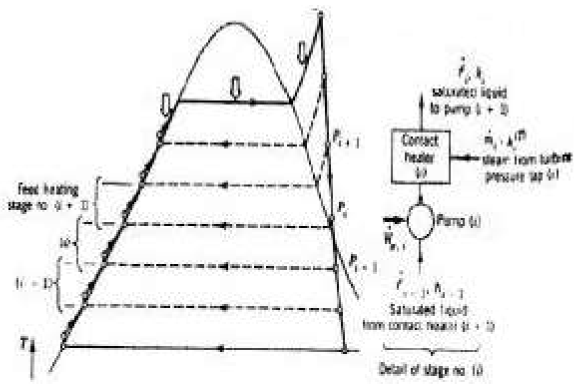

Fig. 2: Regenerative cycle with open feed water heater

- Feed water combination with injected steam from turbine.
- Heat transfer among two above mentioned processes, because of difference in temperature.

Therefore at certain conditions, parameters of optimization cycle performance will depend on maximizing cycle efficiency and minimizing mentioned irreversibility's.

Irreverssibilitis: Irreversibility values for the whole cycle and its components and writing the second rule are determined as follows [7]:

Condenser: Condenser irreversibility with due attention to the fact that passing flow through it is assumed a unit, equals:

$$\dot{I}_{condenser} = T_0\left[s_0 - s_3 + \frac{h_3 - h_0}{T_0}\right] \tag{4}$$

Feed Water Heaters: irreversibility of heater number i, is gained through following relationship:

$$\dot{I}_{heater} = T_0\left[\left(1+\sum m_i\right)s_i - \left(1+\sum m_{i-1}\right)s_{i-1} - m_i s_i^{(T)}\right] \tag{5}$$

In which $S_i^{(T)}$ shows the injected steam entropy from turbine to heater number I.

Boiler: Boiler irreversibility, considering that flame temperature is T_f, is gained through following relationship:

$$\dot{I}_{boiler} = T_0\left(1+\sum m_i\right)\left[\left(s_2 - s_n\right) - \frac{\left(h_2 - h_n\right)}{T_f}\right] \tag{6}$$

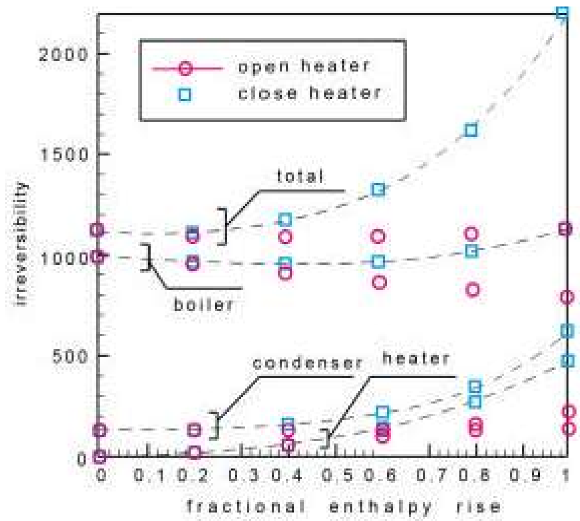

Fig. 3: Irreversibility of steam cycle and its components, in two states

Turbine: Turbine irreversibility is the sum of its processes' irreversibility's, in which steam flow in every step is reduced, as compared with previous steps.

$$\dot{I}_{turbine} = T_0\sum_{i=1}^{n}\left[\left(1+\sum m_i\right)\left(s_i^{(T)} - s_{i+1}^{(T)}\right)\right] \tag{7}$$

Pumps irreversibility is waived against turbine irreversibility.

Regenerative Cycle with Open Feedwater Heaters and Irreversibility of the Whole Cycle: Both heaters- open feed and close feed- cause the maximum average temperature ($T_{H,ave}$) to increase and therefore the heating efficiency increases as well and this process reduces the whole irreversibility of the cycle [6, 8]. In Fig. (3) the irreversibility of cycle and its components is demonstrated, for two types of open feed and close feed heater. In this graph only one of the heaters is used.

In this graph and other graphs of this section, the independent variable is the whole amount of relative preferment of water feed entropy (X_n). This variable is determined through following relationship.

And also if more than one heater is used, the position of other heaters can be appointed. By investigating the graph, it becomes clear that irreversibility rate of the whole cycle and its components, is more in close heater than in open heater, in such a way that in optimum state this difference reduces to 3%. But when (X_n) increases, this difference goes high rapidly, so when

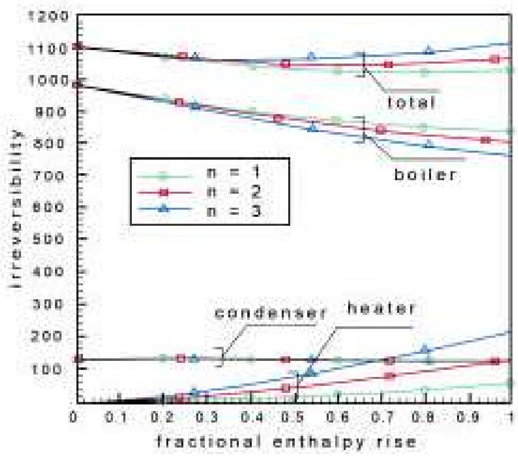

Fig. 4: Irreversibility rate for regenerative cycle and its components, for different heaters

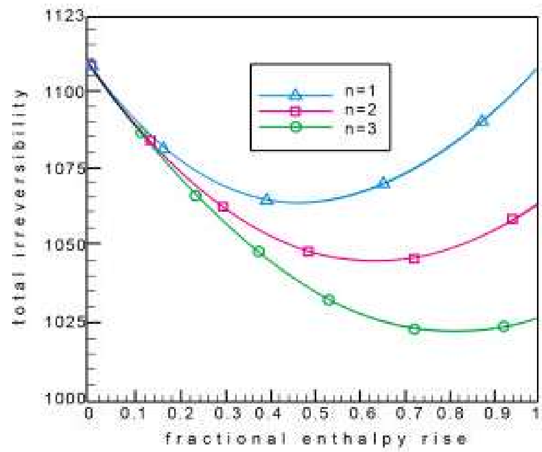

Fig. 6: Irreversibility rate of the whole cycle for different heater

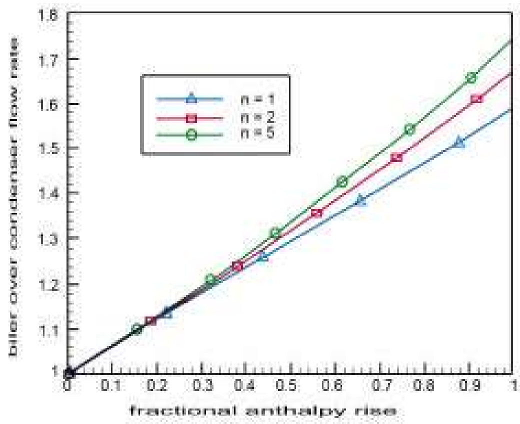

Fig. 5: Relative efficiency increase values for different heater

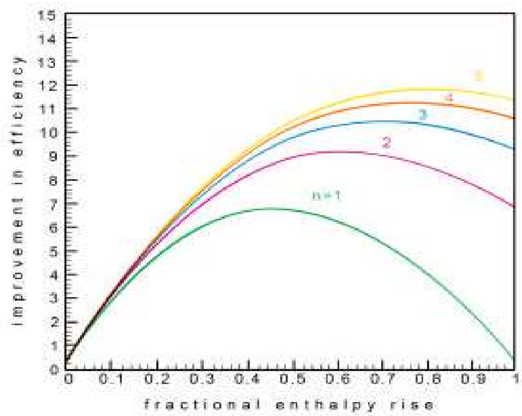

Fig. 7: Relative efficiency increase values for different heaters

X_n = 1, the difference will be more than 95%. A good reason for this occurrence is the existence of better heat transfer features and also combination of feed water and injected steam for open heaters.

Optimization Results and Comparing Them to Hywood and Habib Methods: At this part the results of steam cycle optimization for open feed water heaters is represented. Later we will compare them with the results of Haywood [1] method for open heaters and also with Habib and his colleagues' [2] for close feed water heaters. Optimization for ideal turbine cycle is accomplished with the following characteristics: P_L=0.1 and P_H=100 bar.

Fig. (4) illustrates the irreversibility rate of cycle and its components in three states of 1,5 and 2 feed water heater. As shown in the figure, when the number of heaters increases, the whole cycle irreversibility decreases and as expected for all (X_n), the optimum value of (X_n) increases. About cycle components we can observe that, in condenser, assuming that the flow passing it is unit, the irreversibility rate remains unchanged.

The irreversibility rate of the sum of heaters, by increasing the number of heaters, declines remarkably. And this is the main reason for irreversibility rate reduction of the whole cycle. But about boiler it is different, when heaters increase, irreversibility rate increases as well. The reason why this happens gets clear if we investigate Fig. (5). In this figure there are diagrams that relate to the ratio of the flow passing boiler to condenser. As the figure shows, the flow ratio increases by adding the number of heaters and this occurrence causes the irreversibility rate of boiler to increase.

Fig.(6) demonstrates the irreversibility rate of the whole cycle separately and more vividly. And the increase of optimum value of (X_n) by adding the number of heaters is crystal clear. In optimum state, the amounts of irreversibility rate reduction for type one, two and five heaters are 4, 6 and 8 percent, respectively. According to the results reached by Habib and his colleagues' the total of irreversibility is obtained respectively 1100KW, 1300KW, 1000KW for the values of n=1,2,3. By comparing the results of this heater and Fig. (6), we reemphasize that open heaters' application offer better optimum conditions.

Fig. (7) Shows the amount of relative increase of heating efficiency. According to diagrams, it is clear that when the number of heaters increase, efficiency increase becomes intense and in optimum state the value of (X_n) increases with the number of heaters. According to diagram in this figure, the optimum value of (X_n) completely conforms with values related to the irreversibility diagrams. This conformity confirms the sameness of energy analysis method and exergy Method. When there is one heater, X_n=0.47 is the optimum value of enthalpy relative increase, while in Haywood Method this value is estimated X_n=0.5 with 6% degree of error. In Haywood Method, when there are two and five heaters, degree of error is less than 6% and around 2/5%, respectively. These figures show that when the numbers of heaters increase, in Haywood Method [1], estimated value approaches to reality. Generally because changes are less in the area around optimization point, the mentioned error is acceptable for determining optimum situation of heaters. Also, the amount of heating efficiency with regard to simple cycle, for the conditions when heaters are one, two and five is 6%, 9% and 12%, respectively.

With due attention to the relative efficiency increase for the close heater application depending to Habib and his colleagues' can be seen that the optimal efficiency for n = 1 is negative, -5% and for n = 2, -3% and the positive values is obtained for n = 3 to n = 5 that the optimal efficiency for n = 5 is about 5%. Here again it's clear that efficiency is more in open heaters. It should be mentioned that in close heaters and for some of the values, relative efficiency has negative value while these values are always positive for open heaters.

The Results: We talked about regenerative cycle using two methods: one was energy analysis and heating efficiency diagrams and the other was the exergy Analysis Method and cycle irreversibility diagrams. It was observed that both methods act similarly in determining the optimum condition of heaters. Exergy Analysis Method not only evaluates the whole cycle, but it investigates the behavior of components separately and specifies the level of their effect on inefficiencies of the whole cycle. For instance, irreversibility diagram clarifies that boiler's share in irreversibility of the whole cycle is more than condenser. While Energy Analysis method suggests that the main reason of efficiency reduction of cycle is condenser and be aware that this recognition is wrong.

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