Optimization and Exergy Analysis of Advanced Rankine Cycle Using Internal Heat Exchanger Cycle and Internal Regenerative Heat Exchanger Cycle

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Abstract: In this paper, we investigate the optimization of a Rankine cycle using energy and exergy methods. We also introduce the irreversibility of the Rankine cycle and its components which are used in exergy analysis methods. Advanced Rankine cycle and optimization methods are discussed which investigate the increase in pressure and maximum temperature of the cycle, as well as implementations of heat exchangers including internal heat exchanger as a regenerator in order to optimize the Rankine cycle. Finally, by writing a computer code based on the relations presented, the results of optimization and exergy analysis of internal heat exchanger cycle and internal regenerative heat exchanger cycle will be provided and discussed. Optimization of ideal steam turbine cycle has been done with the following specifications:

- Maximum pressure of the cycle \( P_H = 100 \text{bar} \)
- Minimum pressure of the cycle \( P_L = 0.1 \text{bar} \)
- Maximum temperature of the cycle \( T_H = 550^\circ \text{C} \)
- Flame Temperature \( T_F = 550^\circ \text{C} \)
- Ambient Temperature \( T_O = 20^\circ \text{C} \)

Key words:

INTRODUCTION

Exergy analysis is applied as a powerful tool for analyzing energy systems and power generating machines. In this method, the efficiency of different sources of energy and the factors reducing this efficiency are investigated completely and precisely. Using exergy method, we can precisely measure the losses in a cycle and its deficiency and determine the locations, types and magnitudes of wastes and losses. This can be used for different kinds of systems, whether simple or complex. Exergy analysis method also gives precise measurement of the efficiency of complex compound systems and open systems.

Notwithstanding, the processes of a cycle affect each other and losses at one part can affect others parts. The advantage of exergy method is its ability to predict the effect of any part on other parts of the system and it can specify the relationship between losses.

Internal Heat Exchanger Cycle:

Generally, internal heat exchanger cycle in a steam cycle increases average maximum temperature \( T_{H,ave} \) and as a result efficiency increases, but using internal heat exchanger has another effect and that is the increase of average minimum temperature \( T_{L,ave} \), which is one of the factors decreasing efficiency; thus, in order to use internal heat exchanger in a steam cycle, there is an optimum condition in which efficiency will be maximized (Figure 1). The figure illustrates thermal efficiency versus reheat pressure.

The range of reheat pressure varies between minimum pressure \( P_H \) and maximum pressure \( P_L \). The point at the rightmost side of the graph depicts cycle efficiency without internal heat exchanger which is approximately 41%; with the decrease of reheat pressure from the maximum pressure \( P_H \), efficiency gradually increases.

In other words, the effect of increase in \( T_{H,ave} \) surpasses the effect of increase in \( T_{L,ave} \). The optimum pressure is \( P_{opt} = 20 \text{bar} \) which is 10% of the maximum pressure. Maximum efficiency is approximately 4.5% higher than the single cycle efficiency; decreasing pressure from this point on gradually decreases efficiency which signifies diminution of the effect of increase in \( T_{H,ave} \) versus increase in \( T_{L,ave} \) so that in the pressure of \( P = 2.4 \text{bar} \), efficiency is approximately equal to the efficiency of a cycle without internal heat
exchanger. With more decrease of pressure, efficiency decreases again so that at pressures close to minimum pressure \( P_L \), about 30% decrease of efficiency is observed which is a considerable amount.

Considering the above issues, the significance of implementing an internal heat exchanger is evident and generally, implementing an internal heat exchanger for the pressures higher than 20 to 25 percent of maximum pressure \( P_H \) increases cycle efficiency in comparison with the condition where there is no internal heat exchanger.

![Efficiency of internal heat exchanger cycle versus reheat pressure](image1)

**Fig. 1:** Efficiency of internal heat exchanger cycle versus reheat pressure

**Steam Turbine Cycle with Two Internal Heat Exchangers:**

Increasing the number of heat exchangers leads to an additional increase in the average maximum temperature \( T_{H,ave} \) and consequently increases cycle efficiency. In this condition, like the previous cycle with one internal heat exchanger, each of the heat exchangers has an optimum working pressure. Figure 2 plots thermal efficiency of the cycle versus second reheat pressure \( PR2 \) and for a number of mid to high pressures \( PR1 \). The solid line indicates the condition where \( PR1 \) reaches the maximum pressure \( P_H \) which is in fact the same single internal heat exchanger condition and is equivalent to Figure 1 in which the rightmost point indicates cycle efficiency without internal heat exchanger.

![Steam cycle efficiency versus first and second reheat pressure](image2)

**Fig. 2:** Steam cycle efficiency versus first and second reheat pressure
With the decrease of $PR_1$ from maximum pressure ($P_H$), efficiency gradually increases and maximum efficiency is obtained at the pressures of $PR_1 = 21\text{bar}$ and $PR_2 = 5\text{bar}$ which shows 7.5% more efficiency than the condition with no internal heat exchanger and 3% more efficiency that the condition with one internal heat exchanger; thus, it is revealed that the effect of adding a second internal heat exchanger on increasing efficiency is less than the effect of adding just one. With the decrease of $PR_1$, maximum efficiency will decrease too; so much that it will be less than the efficiency in the condition with no internal heat exchanger and therefore implementing two internal heat exchanger may have an inverse effect unless they are set at optimum pressure. Figure 3 illustrates the values of efficiency in various $PR_1$ pressures versus $PR_2$.

![Figure 3: Maximum efficiency values for optimum pressures of the first heat exchanger versus second heat exchanger pressure](image)

Maximum efficiency occurs at the optimum pressure of $PR_2 = 5\text{bar}$. At the right side of this point there is a broad range of optimum efficiency values for $PR_1$ and their maximum decrease in relation to maximum pressure occurs at $PR_2 = 20\text{bar}$ and is equal to 3%. Therefore it is possible to choose a second internal heat exchanger with acceptable efficiency at this broad range. However, in the left side of the maximum efficiency point and for pressures less than optimum pressure, efficiency drops quickly.

Considering the results of these three graphs, it is revealed that implementing the internal heat exchanger at the interval between optimum pressure and maximum pressure ($P_H$) is appropriate, but it is not useful at pressures lower than optimum pressure and particularly at pressures close to minimum pressure ($P_L$).

Figure 4 represents constant efficiency lines for pressures of the first and second heat exchanger. This graph is helpful in that it enables choosing pressures of the first and second heat exchangers at various efficiency levels. As seen in the graph, the more it moves toward inner loops, the more efficiency increases and the condition with maximum efficiency is illustrated as a dot in the innermost loop. Various factors affect the choice of optimum reheat pressure. Here we investigate the effect of parameters such as reheat temperature, temperature and maximum cycle pressure on optimum reheat pressure.

**The Effect of Reheat Temperature:**

The maximum temperature of working fluid at reheating affects determining optimum reheat pressure. In previous sections, this temperature was assumed to be equal to the maximum temperature of the cycle ($T_H$). Figure 5 plots thermal efficiency versus reheat pressure at three different temperatures.
As seen in the graph, maximum efficiency increases with the increase in reheat temperature and this maximum value occurs at a higher pressure. The degree of increase in efficiency when reheat temperature is equal to the maximum temperature of the cycle, versus the condition close to saturation temperature, is about 4.5%. With the decrease of pressure from the optimum pressure, the three plots converge so that in pressure of about \( PR = 0.77 \text{bar} \), the efficiency values for the three conditions become equal; at pressures lower than this, the sequence of plots is inverted so that with the decrease of reheat temperature, efficiency increases. The reason is the same as we mentioned in previous sections; with the decrease of reheat temperature from a given value, thermal efficiency drops to values less than the condition in which there are no internal heat exchangers. That is in this condition, efficiency of the cycle without heat exchanger is more than the efficiency of an internal heat exchanger cycle; thus, in this condition lower reheat temperatures suggest approaching the cycle without internal heat exchangers and efficiency increases.

Figure 6 depicts constant efficiency lines versus reheat temperature and pressure. As seen in the graph, there is a minimum reheat temperature for a certain efficiency which determines that efficiency. In other words, at each given reheat temperature, a maximum efficiency can be obtained which occurs at a certain reheat pressure and this pressure intangibly increases with the increase of the related temperature.

Figure 7 presents thermal efficiency versus reheat pressure at different \( T_H \) temperatures. Maximum efficiency increases with the increase in the temperature of \( T_H \), but according to the figure, its corresponding pressure decreases. The increase in the temperature of \( T_H \) from 450°C to 550°C leads to about 5% increase in the efficiency of the internal heat exchanger cycle.
Figure 8 presents constant efficiency lines for reheat pressure and maximum temperature of the cycle. As seen in the graph, at each $T_H$ temperature a distinct maximum efficiency can be obtained.

**The Effect of Maximum Pressure of the Cycle ($P_H$):**

The efficiency of internal heat exchanger cycle increases with the increase of $P_H$, which is evident in Figure 9 in which efficiency is plotted versus reheat pressure at different values of $P_H$. As seen in the figure, with the increase of $P_H$, maximum efficiency occurs at higher reheat pressures. With the increase of pressure from 100 bar to 200 bar, efficiency increases to about 5.5%.

Figure 10 represents constant efficiency lines for reheat pressure and maximum pressure of the cycle. Like the previous two conditions, at a given $P_H$ pressure, a certain maximum can be obtained (as seen in the figure).
Fig. 8: Constant efficiency lines for reheat pressure and maximum temperature of the cycle

Fig. 9: Thermal efficiency versus reheat pressure at different maximum pressures

Fig. 10: Constant efficiency lines for reheat pressure and maximum pressure of the cycle
Reference

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Habib, M.A. and S.M. Zubair, "second law-based thermodynamic A nalysis of Regenerative-reheat rankine cycle power plants"


Nov 22, 2012 – In the paper presented is an idea of organic Rankine cycle (ORC) operating with supercritical parameters and so called dry fluids.

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