Development of a computer code for a regenerative Rankine cycle analysis

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1. Introduction

A regenerative Rankine cycle can increase the thermal efficiency of a steam system without increasing the steam pressure and temperature. The regenerative process involves heating the feedwater on its return trip to the steam generator by extracting steam at various stages of the turbine and transferring the energy to the feedwater via a feedwater heater. Some real plants use more than five feedwater heaters to enhance the cycle efficiency. However, the optimum number of feedwater heaters required is determined by balancing the efficiency improvement against the capital investment for a given cycle.

In the present study, the computer code, TAOPCS, for the thermodynamic analysis of a regenerative steam cycle was developed to optimally design and accurately analyze the behavior of the power conversion system of Korea Advance Liquid Metal Reactor (KALIMER)[1]. In order to understand the functions and the characteristics of the code, the main features of the TAPCS were described and the example results are presented in this paper.

2. Description of a regenerative Rankine cycle

As shown in Figure 1, the cycle consists of five major components e.g. steam generator, turbine, condenser, feedwater heaters, and pumps. The feedwater is heated at the steam generator and is converted into a high pressure and high temperature steam. The steam is changed into a low pressure vapor pass through the turbine to generate mechanical power. The saturated liquid from the condenser is pressurized to P_2 by a condenser pump and then it is fed to the feedwater heater. The feedwater heaters allow the liquid to be heated by the steam extracted from the turbine. There are two kinds of feedwater heater : one is a open type(OFWH) in which the streams are directly mixed, the other is a closed(CFWH) one in which the heat transfer occurs through the tube walls. After leaving the feedwater heater, the feedwater is pressurized in the feedwater pump and then pumped to the steam generator.

3. Energy analysis of the cycle

The TAPCS reflects the inefficiencies or irreversibilities of the turbine and pump to make the analysis more descriptive of an actual operation.

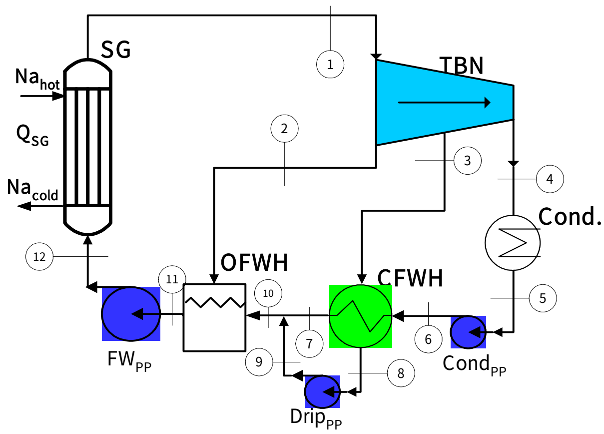

Figure 1 A Schematic representation of a regenerative Rankine cycle

The adiabatic efficiencies of the turbine and pump were assumed as that suggested in the literature [2]. In this code, we considered that the steam is extracted at two stages for regeneration and the steam is transferred to one OFWH and one CFWH, respectively. The heaters are also assumed to be well insulated, therefore, they don't involve any work or heat transfer.

The thermal efficiency of this cycle, η_{cycle}, is defined as :

$$\eta_{cycle} = \frac{\dot{W}_{TBN} - \dot{W}_{pump}}{Q_{SG}} \times 100 \qquad (1)$$

where $\dot{W}_{TBN}$ and $\dot{W}_{pump}$ are the turbine output and required pumping power for the pumps respectively. For the cycle outlined in Figure 1, the turbine output can be written as;

$$\dot{W}_{TBN} = \dot{m}_2(h_1 - h_2) + (1 - \dot{m}_2)(h_1 - h_3) + \dot{m}_4(h_1 - h_4) \qquad (2)$$

where $\dot{m}_i$ is the flow rate and the specified numbers, as subscript, denote the cycle points in Figure 1. If we look at the conservation of the mass through the turbine, we find following relation:

$$\dot{m}_1 = \dot{m}_2 + \dot{m}_3 + \dot{m}_4 \qquad (3)$$

The enthalpies at point 2 and 3 can be calculated by equation4 (4) and (5)

$$h_2 = h_1 - \eta_{TBN}(h_1 - h_2^{id}) \qquad (4)$$

$$h_3 = h_1 - \eta_{TBN}(h_1 - h_3^{id}) \quad (5)$$

where h_2^{id} and h_3^{id} represent the enthalpy after a reversible adiabatic expansion through the turbine. The power required to convey the flow rate through the each pump is determined from the equation,

$$\dot{W}_{pump} = \frac{\dot{m}\ \Delta P_i}{\rho\ \eta_{pump}} \quad (6)$$

where ΔP_i is the pressure drop for each pump and η_{pump} is the adiabatic efficiency of the pump.

The exit enthalpies of the OFWH and the CFWH are given by:

$$h_7 = h_7 + \frac{\dot{m}_3 (h_3 - h_8)}{\dot{m}_4} \quad (7)$$

$$h_{11} = \frac{\dot{m}_2 h_2 + \dot{m}_{10} h_{10}}{\dot{m}_{11}} \quad (8)$$

where h_8 is the saturation liquid enthalpy at the pressure of P_2.

4. Results and discussion

In a regenerative steam cycle, the initial steam pressure and temperature, extracting steam pressure, condenser pressure, and the number and type of feedwater heater may have noticeable effects on the cycle efficiency. Sometimes, it should be determined which combination among the independent variables will provide the maximum efficiency. For showing an example, a preliminary analysis for the condition of the KALIMER power conversion system has been done using the methodology developed in the study. The major parameters for the calculation are summarized in Table 1.

Table 1 Input values for the analysis of the KALIMER

Turbine inlet temperature	463.4 °C
Steam generator inlet temperature	230 °C
1st Extraction pressure	5.5 MPa
2nd Extraction pressure	1 MPa
Adiabatic efficiency of turbine	90 %
Adiabatic efficiency of pump	80 %

In figure 2, the rate of heat required and the efficiency are plotted against the fraction of the mass of the extracting steam. The rate of heat decreases almost linearly with the mass fraction while the efficiency increases slightly. Figure 3 shows the cycle efficiency when the pressures of the turbine inlet and condenser outlet were varied. There is an optimum operating point in the relationship between pressure of the turbine inlet and the condenser outlet. The thermal efficiency increases as the condenser pressure decreases. However, as might be expected, the efficiency increases with the pressure at the turbine inlet.

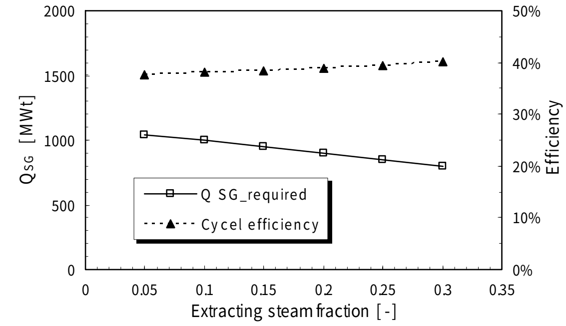

Figure 2 Effect of extracting steam fraction on the characteristics of a regenerative Rankine cycle.

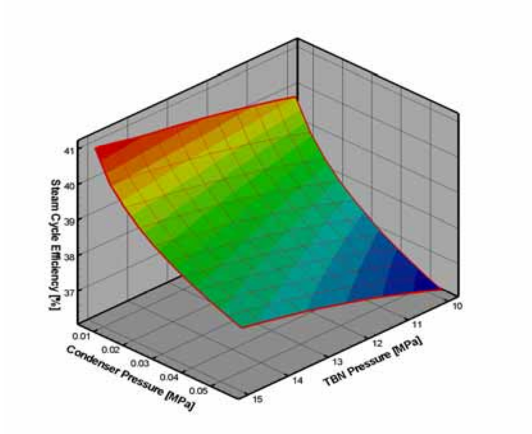

Figure 3 Effect of turbine inlet and outlet pressure on the thermal efficiency.

5. Conclusion

In this paper, we developed a computer code to analyze the thermodynamic characteristics of a regenerative Rankine cycle. The code TAPCS permits a fast thermodynamic optimization of the cycle if one or more of the parameters or properties are varied. Therefore, it is expected that the code TAPCS can be utilized for various purposes in establishing the concept of the KALIMER power conversion system.

AKNOWLEDGEMENT

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