Thermodynamic Analysis of a Rankine Cycle Powered Refrigeration System Using Mid-Low Temperature Geothermal Sources

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Abstract. To efficiently utilize mid-ow temperature geothermal sources, an organic Rankine cycle-vapor compression refrigeration (ORC/VCR) system was employed and a thermodynamic model was developed. Six working fluids of R290, R600, R600a, R601, R601a and R1270 were analyzed and evaluated in order to identify suitable working fluids which may yield high system efficiencies, and system design and influencing factors were researched with the overall COP and working fluid mass flow rate of per kW cooling capacity as key performance indicators. The results show that R601 is the best working fluid for the ORC/VCR system as the geothermal water temperature is between 60 to 90 °C. When the geothermal water temperature reaches 90 °C and the other input parameters are in typical values, the overall COP of the R601 case reaches 0.48.

1. Introduction

Geothermal energy, which is huge nature energy under the earth, has been significant one of the renewables along with the development of energy in the 21st century. Comparing with other renewables, the advantages of geothermal energy are stability and continuity. Therefore, in the future energy structure in China, geothermal energy will play the role which supplies the stable, continuous base load.

In recent years, researchers carried out a lot of research on mid-low temperature geothermal power generation, results have shown that ORC is one of the most convenient and efficient technology. To the best of the author’s knowledge, the more and more mid-low temperature geothermal source found widely in most regions have not received much attention for ORC system in VCR driven by mid-ow temperature geothermal sources.

This paper aims to investigate the potential of an ORC-VCR system using mid-ow temperature geothermal sources with R245fa as working fluids for both the ORC and VCR cycles. And typical case and parametric studies are performed by using Engineering Equation Solver (EES) software. It will also present it’s fundamental concept and discusses it’s limitations, environmental & economic considerations, and energy conversion performance concept.
2. System design

![Figure 1. Flow chart of the system](image1)

![Figure 2. T-S diagram for ORC/VCR system](image2)

As shown in Figure 1. and Figure 2. , the ORC/VCR system investigated here consists of two cycles, the ORC identified as 1-2-3-4-1 and the VCR cycle as 5-6-3-7-5. The working principle of this system is as follows: In the ORC, the working fluid is heated and vaporized with low boiling point in the generator by the geothermal water, and then flows into the expander to drive a vapor compressor for the VCR cycle. Afterwards, the working fluid enters into the condenser, where it is condensed to subcooling state. The cooled working fluid at the condenser is pumped back to generator where it is again vaporized to complete the cycle. In the VCR, the working fluid in the evaporator vaporizes and then the working fluid vapour flows into the compressor, and subsequently into the condenser. At last, the cool liquid working fluid at the condenser back to the evaporator through the throttle valve and then the cycle is completed.

3. Thermodynamic analysis

For simplicity to develop the thermodynamic models, an assumptions are made as follows: steady-state flow in each component, the state is considered to be steady; heat and friction losses through the ORC/VCR system are negligible.

For ORC:
\[ W_{\text{exp}} = m_{\text{ORC}} (h_1 - h_2) \eta_{\text{exp}} \] (1)
\[ W_{\text{pump}} = \frac{m_{\text{ORC}} (h_4 - h_3)}{\eta_{\text{pump}}} \] (2)
\[ W_{\text{net}} = W_{\text{exp}} - W_{\text{pump}} \] (3)
\[ Q_{\text{geo}} = m_{\text{ORC}} (h_1 - h_4) \] (4)
\[ \eta_{\text{ORC}} = \frac{W_{\text{net}}}{Q_{\text{geo}}} \] (5)

For VCR:
\[ Q_{\text{evap}} = m_{\text{VCR}} (h_5 - h_7) \] (6)
\[ W_{\text{comp}} = \frac{m_{\text{VCR}} (m_3 - m_{\text{in}})}{\eta_{\text{comp}}} \] (7)
\[ W_{\text{comp}} = W_{\text{net}} \] (8)
\[ COP_{\text{VCR}} = \frac{Q_{\text{evap}}}{W_{\text{comp}}} \] (9)

The overall performance of ORC/VCR is defined as:
\[ COP_{\text{sys}} = \eta_{\text{ORC}} COP_{\text{VCR}} \] (10)
\[ MCE = \frac{m_{\text{ORC}} + m_{\text{VCR}}}{Q_{\text{evap}}} \] (11)

4. Results and discussion
As shown in Table 1, the input parameters and boundary conditions are presented. A computer program in By EES (Engineering Equation Solver), is developed to the thermodynamic performance of the ORC/VCR systems are simulated with R290, R600, R600a, R601, R601a and R1270 as working fluids under various operating conditions. The analysis results are provided in Figure 3-5, it also note that in the analysis, the input data are same as the typical values given in Table 1, except that the parameters whose effect are discussed varies in the ranges.
Table 1. Input parameters and boundary conditions

| Parameter                  | Typical value | Ranges     |
|----------------------------|---------------|------------|
| Mass flow rate of working fluid | 1.0 kg/s     | —          |
| geothermal temperature      | 80 °C         | 60–90 °C   |
| Evaporation temperature     | 5 °C          | -15–15 °C  |
| Condensation temperature    | 40 °C         | 30–55 °C   |

Figure 3. Shows the effects of the geothermal temperature on the COPsys and Mcc. It can be seen that when the geothermal temperature rises, the COPsys of the ORC/VCR system also increases. With the geothermal temperature at 90 °C, the maximum overall thermal efficiency-COPsys for the R601 case is 0.480, which owing to the higher critical temperature of the organic and larger than that of the R290, R600a, R601, R601a and R1270 cases by about 29.9%, 3.9%, 12.4%, 1.45% and 39.7% respectively. And the Figure 3 also shows that the Mcc generally decreases with the geothermal temperature increasing for the six working fluids, and the minimum data is seen in the case of R601 within the temperature range (60–90 °C) considered, followed by R600, R601a, R600a, R290 and R1270.

Figure 3. Effect of geothermal temperature on COPsys and Mcc

Due to that the condensation temperature has influences on both of the two cycles, the condensation temperature has a significant impact on the ORC/VCR system performance, as shown in Figure 4. In order to have good efficiencies in the two cycles, high values are usually undesirable because that the overall heat rejection is determined by the condensation temperature. Therefore, it can be found from the Figure 3, that when the condensation temperature increases, it will cause the COPsys decreases, which results in an increase in the Mcc. In comparison, the case of R601 is more preferable to that of R290, R600a, R601, R601a and R1270. The COPsys of the ORC/VCR systems using R290, R600a, R601, R601a and R1270 as working fluids are 0.131, 0.165, 0.1767, 0.1737, 0.151 and 0.126 respectively when condensation temperature at 55 °C. Under the same operating conditions, the minimum Mcc is also found in the case of R601 with the value of 0.0185 kg/(s kW), and the maximum occurs in the case of R1270 with the value of 0.0347 kg/(s kW).
Figure 4. Effect of condensation temperature on COPsys and Mcc

Figure 5. Effect of evaporation temperature on COPsys and Mcc

5. Conclusion

An ORC/VCR system using mid-low temperature geothermal sources is employed in this paper, and the effects of six working fluid such as R290, R600, R600a R601, R601a and R1270 with geothermal temperature, condensation temperature evaporation temperature on the system performance were analyzed by developing the thermodynamic models. The results show that as the geothermal temperature and the evaporation temperature increase, the COPsys increases whereas the Mcc
decreases, and the opposite is true for the condensation temperature. Overall, with the COPsys and Mcc as key performance indicators, it can be concluded that the best one is R601, followed by R600, R601a, R600a and R290, and R1270 is the worst. With the geothermal temperature at 90 °C and the other input parameters in typical values, the COPsys for the R601 case reaches 0.480. A conclusion can be drawn by the results that using ORC /VCR system for refrigeration from mid-low temperature geothermal sources is feasible.

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