Parametric optimization and comparative study of organic Rankine cycle (ORC) for low grade waste heat recovery

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A R T I C L E   I N F O

Article history:
Received 31 July 2007
Received in revised form 5 April 2008
Accepted 28 October 2008
Available online 31 December 2008

A B S T R A C T

Organic Rankine cycles for low grade waste heat recovery are described with different working fluids. The effects of the thermodynamic parameters on the ORC performance are examined, and the thermodynamic parameters of the ORC for each working fluid are optimized with exergy efficiency as an objective function by means of the genetic algorithm. The optimum performance of cycles with different working fluids was compared and analyzed under the same waste heat condition. The results show that the cycles with organic working fluids are much better than the cycle with water in converting low grade waste heat to useful work. The cycle with R236EA has the highest exergy efficiency, and adding an internal heat exchanger into the ORC system could not improve the performance under the given waste heat condition. In addition, for the working fluids with non-positive saturation vapor curve slope, the cycle has the best performance property with saturated vapor at the turbine inlet.

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1. Introduction

In recent years, there has been a great deal of waste heat energy being released into the environment, such as exhaust gases from turbines and engines and waste heat from industrial plants, which lead to serious environmental pollution. In addition, there are also abundant geothermal resources and solar energy available in the world. These heat sources are classified as low grade heat sources. Therefore, more and more attention has been paid to the utilization of low grade waste heat nowadays for its potential in reducing fossil fuel consumption and alleviating environmental problems.

Since conventional steam power cycles cannot give a better performance to recover low grade waste heat, the organic Rankine cycle (ORC) is proposed to recover low grade waste heat. There are several advantages in using an ORC to recover low grade waste heat, including economical utilization of energy resources, smaller systems and reduced emissions of CO₂, NOₓ and other atmospheric pollutants. The main advantage of the ORC is its superior performance in recovering waste heat with a low temperature [1].

The ORC is not a new concept [2], and much research has been conducted on it. Firstly, it is important to select a proper working fluid from the many different working fluids for recovering a given waste heat. Drescher and Bruggemann [3] investigated the ORC in solid biomass power and heat plants. He proposed a method to find suitable thermodynamic fluids for ORCs in biomass plants and found that the family of alkybenzenes showed the highest efficiency. Saleh et al. [4] studied the thermodynamic performances of 31 pure working fluids for organic Rankine cycles on the basis of the BACKONE [5,6] equation of state. Chen et al. [7] examined the performance of the CO₂ trans-critical power cycle utilizing energy from low grade waste heat in comparison to an ORC using R123 as working fluid. They found that when utilizing the low grade heat source with equal mean thermodynamic heat rejection temperature, the carbon dioxide trans-critical power cycle had a slightly higher power output than the ORC. Liu et al. [8] discussed an analysis of the performance of organic Rankin cycles subjected to the influence of working fluids. They investigated the effects of various working fluids on the thermal efficiency and on the total heat recovery efficiency. Hung [9] explored working fluids for organic Rankine cycle to recover waste heat, including benzene, toluene, p-xylene, R113 and R123. He indicated that p-xylene showed the highest efficiency while benzene showed the lowest, and p-xylene had the lowest irreversibility in recovering a high temperature waste heat while R113 and R123 had a better performance in recovering a low temperature waste heat. Hung et al. [10] analyzed parametrically and compared the efficiencies of ORCs using cryogens such as benzene, ammonia, R11, R12, R134a and R113 as working fluids. The results showed that for operation between isobaric curves, the system efficiency increased for wet fluids and decreased for dry fluids while the isentropic fluid achieved an approximately constant value for high turbine inlet temperatures, and isentropic fluids were most suitable for recovering low temperature waste heat.

Even though they compared the ORC performance with different working fluids and found the suitable working fluid that had the best performance of the ORC, they did not evaluate the ORC performance under the optimization condition. It is not easy to
evaluate the performance of the ORC with different working fluids under different operating parameters because different operating parameters could result in better or worse performance. Therefore, it is necessary to evaluate the performance of ORCs with different working fluids under their optimization conditions.

Secondly, some researches have focused on performance optimization for the ORC. Madhawa et al. [11] presented a cost effective optimum design criterion for organic Rankine cycles utilizing low temperature geothermal heat sources. They used the ratio of the total heat exchanger area to net power output as the objective function to optimize the ORC using the steepest descent method. They observed that the choice of working fluid could greatly affect the power plant cost. Wei et al. [12] considered the system performance analysis and optimization of an organic Rankine cycle system using HFC-245fa as working fluid and analyzed the thermodynamic performances of an ORC system under disturbances. They found that maximizing the usage of exhaust heat as much as possible was a good way to improve the system net power output. Under the high ambient temperature, the system output performance deteriorated, and the net power output deviated from the nominal value by more than 30%.

They usually used the conventional optimization algorithm to optimize the ORC. The disadvantage of the conventional optimization algorithm is that it is easy to converge to sub-optimal solutions in the process of searching for the optimum, especially for complicated optimization problems.

The main objective of this study is focused on parametric optimization of the ORC for waste heat recovery in order to find a working fluid that could show better ORC performance for waste heat recovery. The effects of parameters on the ORC performance are explored, and the performance of ORC systems with different working fluids is optimized using a genetic algorithm, which is a new optimization method for waste heat recovery in the ORC. The optimum performances of the ORC with different working fluids are compared and analyzed under the same waste heat condition.

2. Thermodynamic analysis of organic Rankine cycle

The ORC system consists of an evaporator, turbine, condenser and pump. It can be classified in two groups according to the level of turbine inlet pressure, including supercritical ORCs and sub-critical ORCs. In the present study, the sub-critical ORCs are investigated.

The sub-critical ORCs are different types according to the shape of the saturated vapor curve in the temperature versus entropy diagram as shown in Figs. 1–4. Figs. 1 and 2 show two types of ORC processes with the negative slope of the saturated vapor curve in the T–S diagram. As is shown in Fig. 1, the working fluid leaves the condenser as saturated liquid (state point 1). Then, it is compressed by the liquid pump to the sub-critical pressure (state point 2) desired in the heat addition process. The working fluid is heated in the evaporator until it becomes superheated vapor (state point 3). The superheated vapor flows into the turbine and is expanded to the condensing pressure (state point 4). At the condensing pressure, the working fluid lies in the two phase region. The two phase fluid passes through the condenser where heat is removed until it becomes a saturated liquid (state point 1). The processes in Fig. 2 are similar to those in Fig. 1 with the only difference being that the state point 4 after expansion in the turbine lies in the superheated vapor region.

Figs. 3 and 4 show the other two types of ORC processes with the positive slope of the saturated vapor curve in the T–S diagram. The state points 1 and 2 correspond to the ORC system in Figs. 1 and 2. Starting from state 2, the working fluid is heated in the evaporator at constant sub-critical pressure until it becomes

![Fig. 1. A type of ORC with negative slope of saturated vapor curve and wet vapor at the turbine outlet.](image-url)
saturated (state point 3) in Fig. 3 or it is superheated (state point 3) in Fig. 4. Then, it is expanded to state point 4, which is in the superheated vapor region.

In the above cycles, if the temperature \( t_4 \) is markedly higher than the temperature \( t_1 \), it may be rewarding to implement an internal heat exchanger (IHE) into the cycles as shown in Fig. 5. This heat exchanger is also represented in Figs. 2–4 by the additional state points 4a and 2a. The turbine exhaust flows into the internal heat exchanger and cools in the heat exchanger in the process (4–4a) by transferring heat to the compressed liquid that is heated in the process (2–2a).

For the cycle performance simulation, it was assumed that the system reaches a steady state, and pipe pressure drop and heat losses to the environment in the evaporator, condenser, turbine and pump are neglected. Because of the thermodynamic irreversibility occurring in each of the components, such as non-isentropic expansion, non-isentropic compression and heat transfer over a finite temperature difference, the exergy analysis method is employed to evaluate the performance for low grade waste heat recovery. Consider \( P_0 \) and \( T_0 \) to be the ambient pressure and temperature as the specified dead reference state. The exergy of the state point can be considered as

\[
E_i = \frac{m}{C_0} \left( \frac{h_1}{C_0} - h_0 \right)
\]

The exergy balance for an open thermodynamic system can be expressed as [13]

\[
\sum E_{\text{input}} - \sum E_{\text{output}} = I
\]

Each process in the ORC can be described as follows:

Process 2 to 3: This is the constant pressure heat absorption in the evaporator. The heat transferred from the waste heat to the working fluid is

\[
Q = m(h_3 - h_2)
\]

If the internal heat exchanger is added, the amount of heat transfer is presented by

\[
Q = m(h_3 - h_{2a})
\]

The exergy loss in the evaporator can be given as

\[
I_{\text{EVP}} = E_{\text{in}} + E_2 - E_{\text{out}} - E_3
\]

Process 3 to 4: This is a non-isentropic expansion process in the turbine. Ideally, this is an isentropic process 3–4s. However, the efficiency of the energy transformation in the turbine never reaches 100%, and the state of the working fluid at the turbine outlet is indicated by state point 4. The isentropic efficiency of the turbine can be expressed as

\[
\eta_{\text{TBN}} = \frac{h_3 - h_4}{h_{3s} - h_{4s}}
\]

The power generated by the turbine can be given as

\[
W_{\text{TBN}} = m(h_3 - h_4)
\]

The exergy loss in the turbine can be given as

\[
I_{\text{TBN}} = E_3 - W_{\text{TBN}} - E_4
\]

Process 4 to 1: This is a constant pressure heat rejection process in the condenser.
The exergy loss in the condenser can be given as

$$I_{\text{COND}} = E_4 - E_1$$

(9)

Process 1 to 2: This is a non-isentropic compression process in the liquid pump. The isentropic efficiency of the pump can be expressed as

$$\eta_{\text{PUMP}} = \frac{h_2 - h_1}{h_2 - h_1}$$

(10)

The work input by the pump is

$$W_{\text{PUMP}} = m(h_2 - h_1)$$

(11)

The exergy loss in the pump can be given as

$$I_{\text{PUMP}} = W_{\text{PUMP}} + E_1 - E_2$$

(12)

If the internal heat exchanger is added, the exergy loss in the IHE is given as

$$I_{\text{IHE}} = E_4 + E_2 - E_{4b} - E_{2b}$$

(13)

The thermal efficiency of the ORC is defined on the basis of the first law of thermodynamics as the ratio of the net power output to the heat addition.

$$\eta_{\text{th}} = \frac{W_{\text{th}} - W_{\text{PUMP}}}{Q}$$

(14)

The thermal efficiency cannot reflect the ability to convert energy from low grade waste heat into usable work. Therefore, we need to consider the exergy efficiency, which can evaluate the performance for waste heat recovery. The exergy efficiency of the ORC system can be given as

$$\eta_{\text{ex}} = \frac{E_{\text{in}} - \sum I - E_{\text{out}}}{E_{\text{in}}}$$

(15)

3. Optimization of the ORC system for different working fluids

For practical operation, the ORC has many parameters that are varied together, presenting a multi-dimensional surface on which an optimum can be found. These parameters have effects on the ORC performance. In the present study, the effects of turbine inlet pressure and temperature on the performance are examined, and the exergy efficiency, which can evaluate the ORC performance, is selected as the objective function for parameter optimization of the ORC.

For cycle performance simulation, assumptions are also made as follows:

1. The temperature of the waste heat source is 145 °C, and the mass flow rate is 15.951 kg/s.
2. The ambient temperature is considered to be 20 °C.
3. The pinch temperature difference in the evaporator can be assumed to be 8 °C.
4. The condensing temperature, which is the minimum temperature in the cycles, is $t_1 = 25$ °C, and the corresponding condensing pressure is $P_{\text{min}}$. The highest temperature, which occurs at the inlet of the turbine, is $t_3$, and the highest pressure in the cycle is the evaporator pressure $P_{\text{max}}$.
5. If an IHE is used, the temperature at the outlet of the IHE on the low pressure side is 5 °C higher than the temperature at the outlet of the pump, i.e., $t_{4b} - t_2 = 5$ °C.
6. The isentropic efficiencies for the turbine and pump are assumed to be 85% and 60%, respectively.

The thermodynamics properties of the working fluid were calculated by REFPROP 6.01 [14], developed by the National Institute of Standards and Technology of the United States. The ORC simulation was performed by using a simulation program written by the authors with Fortran. The iterative relative convergence error tolerance was 0.01%.

The genetic algorithm is employed to optimize the thermodynamic parameters of the ORC system for different working fluids. The genetic algorithm, which was presented firstly by Professor Holland in America [15], is a stochastic global search method that simulates natural biological evolution. Based on the Darwinian survival of the fittest principle, the genetic algorithm operates on a population of potential solutions to produce better and better approximations to the optimal solution. The genetic algorithm differs from the traditional optimization techniques because it involves a search from a population of solutions and not from a single point, and it prevents convergence to sub-optimal solutions in the process of searching for the optimum.

The genetic algorithm encodes a potential solution to a specific domain problem on a simple chromosome-like data structure (which constitutes an individual), where genes are parameters of the problem to be solved. In the present study, floating point coding is used in the genetic algorithm to solve the problem of parameter optimization in the ORC system. Each chromosome vector is coded as a vector of floating point numbers of the same length as the dimension of the search space. The chromosome is defined as a real number vector, $X = (x_1, x_2, \ldots, x_n)$, $j_i \in R$, $i = 1, 2, \ldots, n$, where $n = 2$, $x_1$ is the turbine inlet pressure and $x_2$ is the turbine inlet temperature.

The GA only uses a fitness function to evaluate the adaptability of an individual without external information in the evolution search. The adaptability is expressed by the fitness value. A bigger fitness value means a better adaptability to constraints and a better viability of the individual. A fitness function that is not constrained by definition domain, continuity and differentiability requires that the objective function be defined in the form of a non-negative maximum. In this optimization for the ORC system, the exergy efficiency is selected as the fitness function.

The basic GA operators include the selection operator, crossover operator and mutation operator. The selection operator is responsible for selecting the parents to create the next generation of solutions. The parent is chosen with a probability based on its fitness. The higher its fitness, the higher is the probability of selection. The rank based model is selected for this optimization of the ORC system. The crossover operator is the basic operator for producing new chromosomes in the GA. It produces new individuals that have some parts of both parent’s genetic material. The simple arithmetic crossover was used for this optimization problem due to its very simple operation. The simple arithmetic crossover is presented as follows:

$$\begin{align*}
   & c_1 = a f_1 + (1 - a) f_2 \\
   & c_2 = a f_2 + (1 - a) f_1
\end{align*}$$

(16)

where $a$ is a random number between 0 and 1, $f_1$ and $f_2$ are parents, the individuals selected to crossover each other, $c_1$ and $c_2$ are children, the individuals produced by the crossover. To avoid a local solution, the mutation operator is randomly applied with low probability to modify values in the chromosomes. Random mutation is adopted to optimize the parameters for the ORC system. It is achieved by selecting individuals from the range of the parameter according to the mutation probability.

At each generation, a new set of approximations is created by the process of selecting individuals according to their level of fitness in the problem domain and breeding them together using crossover and mutation operators, which are borrowed from natural genetics. This process leads to the evolution of populations of individuals that are better suited to their environment than the individuals from which they are created. In the present study, the population size, crossover probability, mutation probability
Variations of net power output with various turbine inlet pressure at the respective optimal pressure.

4. Results

Fig. 6 shows the variation of net power output with various turbine inlet temperatures for 10 different working fluids for their respective optimal pressures. It is obvious that as the turbine inlet temperature increases, the net power output for ammonia and water increase correspondingly, but for the other working fluids, temperature increases, the net power output for ammonia and isobutane decreases, but for the other working fluids, there is a maximum net power output. It is obvious that as the turbine inlet temperature increases, the net power output for ammonia and water increase correspondingly, but for the other working fluids, temperature increases, the net power output for ammonia and isobutane decreases, but for the other working fluids, there is an optimum pressure where the net power output reaches the maximum. From Figs. 6 and 7, it can be seen that the turbine inlet parameters have great effects on the performance of the ORC system. Therefore, thermodynamic parameters optimization is conducted for low grade waste heat recovery using the genetic algorithm.

Fig. 7. Variations of net power output with various turbine inlet pressure at $t_3 = 135^\circ$C. The exergy efficiency of the ORC system is used as the objective function. The ORC systems are optimized to operate under their optimum operating conditions for the same given waste heat source and heat sink conditions. The detailed data of the cycles for 10 different working fluids are listed in Table 1.

As shown in Table 1, it is found that the optimized ORC systems for the most working fluids belong to the C type, except water and ammonia. It could be concluded that the lower the exhaust temperature of waste heat, the higher is the exergy efficiency of the ORC system. The R236EA has the highest efficiency with the lowest exhaust temperature in all the working fluids. In addition, the turbine outlet specific volume for R236EA is the smallest of all the working fluids, and this could lead to smaller dimensions of the turbine. It is obvious that the ORC system has better performance than the conventional Rankine cycle with water as working fluid.

It is also evident that the power output would not increase by adding the internal heat exchanger under this waste heat condition because adding the internal heat exchanger would reduce the heat addition of the working fluid, and the available waste heat becomes less than that without the internal heat exchanger. In addition, due to the unchanged power output, the reduced heat addition of the ORC system leads to the thermal efficiency of the ORC system increasing. Since the highest power output is not achieved at maximum cycle thermal efficiency when utilizing a certain waste heat source, increasing the thermal efficiency could not improve the performance of the ORC system in recovering the waste heat.

It is observed that not always does the higher turbine inlet temperature result in greater turbine power output. For optimum operation conditions of the working fluids, such as ammonia and water, with the negative slope of the saturation vapor curves, increasing the turbine inlet temperature could increase the turbine power output and improve the performance of ORC system. However, for the other working fluids with the non-negative slope of saturation vapor curves, such as butane, R123, and R245CA, the turbine inlet temperature should be as low as possible above the boiling point of the working fluid, and the ORC system has the best performance with saturated vapor at the turbine inlet. In addition, the wet fluids are generally not suitable for ORC systems because they may be in the saturated state once they go through a large enthalpy drop after producing work in the turbine, and condensation of the fluids imposes a threat of damage to the turbine. However, the working fluid with the non-negative slope of saturation vapor curve could prevent this disadvantage, and they are more appropriate for ORC systems. The superheater is not needed with these working fluids.

It could be indicated that the most exergy loss takes place in the evaporator. If the internal heat exchanger is used, it could reduce the exergy loss in the evaporator, but it involves an increase in exhaust exergy loss. The reason for this could be that the internal heat exchanger makes the mean transferring heat temperature difference between the waste heat flow and the working fluid smaller in the evaporator, resulting in less thermodynamic irreversibility. In addition, the IHE makes the exhaust temperature increase, resulting in an increase in exhaust enthalpy drop. Therefore, for this waste heat recovery, adding the internal heat exchanger would not be necessary due to having no beneficial effect on the performance of the ORC.

5. Discussion

The main objective of this research is to investigate the performance of the ORC for low grade waste heat recovery. The effects of parameters on the performance of the ORC system are analyzed, and ORC systems with 10 different working fluids are optimized by means of a genetic algorithm. The results indicate that the or-
Table 1  
Comparison of the optimized ORC system with 10 different working fluids.

<table>
<thead>
<tr>
<th>Substance</th>
<th>Unit</th>
<th>Ammonia</th>
<th>Butane</th>
<th>Isobutane</th>
<th>R11</th>
<th>R123</th>
<th>R141B</th>
<th>R236EA</th>
<th>R245CA</th>
<th>R113</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td></td>
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<td>+IHE</td>
<td>-IHE</td>
<td>A</td>
<td>C</td>
<td>+IHE</td>
<td>-IHE</td>
<td>+IHE</td>
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<td>1</td>
<td>1</td>
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<tr>
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<td>154.15</td>
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<td>162.12</td>
<td>167.84</td>
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<td>/</td>
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<td>1.14</td>
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<tr>
<td>I&lt;sub&gt;exg&lt;/sub&gt;</td>
<td>%</td>
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ganic working fluids are superior to water, which is the conventional working fluid for converting low grade waste heat to power. It should be pointed out that only the thermodynamic aspects of the working fluids for ORC processes have been considered. Other aspects such as stability, compatibility with materials in contact, safety, costs and environmental aspects are not discussed in the present study. In the future, the performance of supercritical ORC systems with different working fluids will be explored.

6. Conclusions

In the present study, the effects of parameters on the thermodynamic performance of ORCs for waste heat recovery systems are examined. Parameter optimizations of the ORC systems are performed with 10 different working fluids using a genetic algorithm. In addition, the performances of the ORC systems with different working fluids are compared and analyzed under the same given waste heat condition. The main conclusions can be summarized as follows:

(1) Compared with other working fluids, the ORC system with R236EA has higher exergy efficiency under the same given waste heat condition. In addition, due to less turbine inlet specific volume, the dimensions of the turbine could be designed smaller.

(2) Adding the internal heat exchanger would not improve the performance of the ORC system under this waste heat condition.

(3) It is not always true that the higher the turbine inlet temperature, the greater is the turbine power output. For the working fluids with the non-negative slope of the saturation vapor curves, the turbine inlet temperature should be kept as low as possible above the boiling point of the working fluid, and the ORC system with saturated vapor at the turbine inlet would produce the greatest turbine power.

References