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The effect of different organic fluids on performances of binary slag washing water power plants

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Abstract In this paper, 3 typical organic fluids were selected as working fluids for a sample slag washing water binary power plants. In this system, the working fluids obtain the thermal energy from slag washing water sources. Thus, it plays a significant role on the cycle performance to select the suitable working fluid. Energy and exergy efficiencies of 3 typical organic fluids were calculated. Dry type fluids (i.e., R227ea) showed higher energy and exergy efficiencies. Conversely, wet fluids (i.e., R143a and R290) indicated lower energy and exergy efficiencies, respectively.

Keywords: Slag washing water; Efficiency; Organic fluids; Binary power cycle

Nomenclature

E – energy rate, kW
 Ex – exergy rate, kW
 h – specific enthalpy, kJ/kg
 m – mass flow rate, kg/s

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p	–	pressure, MPa
s	–	specific entropy, kJ/(kg K)
Q	–	heat transfer rate, kW
T	–	temperature, K
W	–	work rate, power, kW

Greek symbols

η	–	energy or first law efficiency, %
ψ	–	flow energy, kJ/kg
ε	–	energy or second law efficiency, %

Subscripts

cw	–	cooling water
$dest$	–	destroyed, destruction
in	–	inlet
out	–	outlet
sww	–	slag washing water
wf	–	working fluid

1 Introduction

Organic Rankine cycle (ORC) is an important technology for conversion of energy which belongs to the low-grade heat resource into electricity. Both ORC and conventional steam Rankine cycle have the same operational principle. The only difference is that ORC uses organic working fluid with lower boiling temperature instead of water of conventional steam Rankine cycle. In utilization of the low temperature heat source, ORC shows great flexibility [1]. There are some low temperature heat sources which can be used for ORC such as solar radiation [2–4], geothermal energy [5–7], biomass combustion [8–10] and industrial waste heat [1,11–13], etc. Recently, some researches about ORC system have been explored [14–16].

In industry the source of waste heat occurs in very large volumes with a wide temperature distribution. For example, water is usually used to cool the slag and the temperature of the cooling-water washing the slag is generally between 80 and 90 °C in steel industry. It can be employed to heat buildings or preheat any other process. Furthermore, it can be used to produce electricity by organic Rankine cycle (ORC).

Slag washing water generally comprises numerous corrosive chemicals, because the binary power cycle is used to recover the waste heat from slag washing water. In this cycle, slag washing water never contacts with the system components except for the heat exchanger and the damaging effects of these chemicals can be prevented by binary power cycle. In a binary

cycle power plant, the heat of slag washing water is transferred to a low boiling point and high vapor pressure organic fluid when compared to water at a given temperature [12,13].

The choice of working fluid affects considerably the system performance, therefore, the organic fluids play a key role in the cycle. The density of the organic fluid must be high either in the liquid or vapour phase. High liquid or vapor density lead to increase of mass flow rate and reduction of the size of equipment [17,18]. If the temperature and other parameters are defined, organic fluids with high latent heat and high density give high unit work output [19]. Low heat capacity of the organic fluid enables a near vertical saturated liquid line which has affected same high latent heat [18]. Briefly, organic fluids with high density, low liquid specific heat, and high latent heat are expected to give a high turbine work output [19].

In this paper, three typical organic fluids were selected as working fluid for a sample slag washing water binary power plants. In this system, the second working fluid obtains the thermal energy from slag washing water sources. Energy and exergy efficiencies of these typical organic fluids were calculated.

2 System description

The schematic representation of the ORC power plant supplied with energy of slag washing water (SWW) of blast furnace is shown in Fig. 1. The binary slag washing water power plant system consists of pump, evaporator, turbine and condenser. In this plant, the following working conditions are assumed for the aim of selecting and screening of optimum organic working fluids based on characteristic operation conditions of binary power cycle. These working conditions are specified considering reality plant operation conditions, since there is now an actual Kalina cycle in operation, it ought to be possible to make a comparison between it and ORC plants that have been in operation for some time and they show parallelism with the reality binary power plants examined by, e.g., [20,21] with respect to being same thermodynamic phase at the same status in the cycle.

For a general steady-state, steady-flow process, the three balance equations, namely mass, energy, and exergy balance equations, are employed to find the heat input, rate of exergy decrease, rate of irreversibility, and energy and exergy efficiencies [22,23]. In general, the mass balance equation

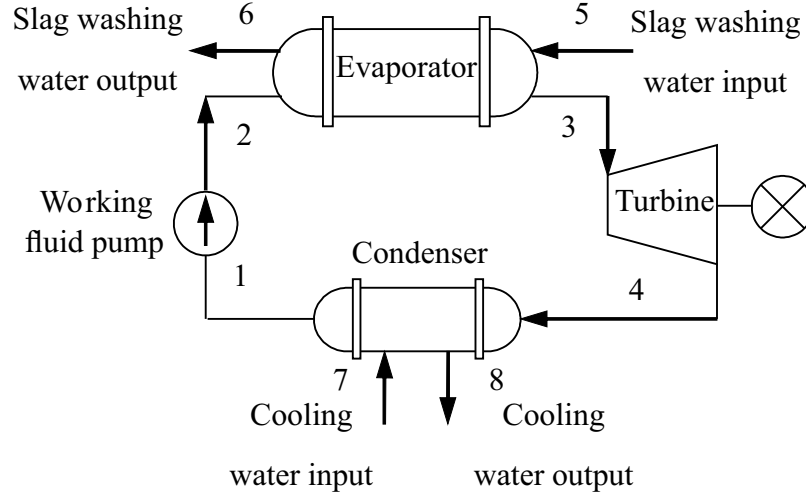


Figure 1: Schematic of analyzed slag washing water binary power cycle.

can be expressed as

$$\sum m_{in} = \sum m_{out} , \quad (1)$$

where m is the mass flow rate and the subscripts in and out stand for inlet and outlet. The general energy balance with negligible kinetic and potential energy changes can be expressed by

$$Q - W = \sum m_{in}h_{in} - \sum m_{out}h_{out} , \quad (2)$$

where Q and W are the heat transfer rate and work rate and h is the specific enthalpy.

The energy efficiency of the system η_{sys} can be defined as the ratio of total net heat input to total work output

$$\eta_{sys} = \frac{W}{Q} . \quad (3)$$

In this context, the specific exergy can be defined as follows:

$$\psi = (h - h_0) - T_0 (s - s_0) , \quad (4)$$

where subscript 0 stands for the restricted reference state, T_0 is the reference state temperature, and h_0 and s_0 are enthalpy and entropy at the restricted reference state of p_0 and T_0 .

Multiplying specific exergy by the mass flow rate of the fluids gives the rate of total exergy:

$$Ex = m\psi . \quad (5)$$

The general exergy rate balance may be expressed as follows:

$$Ex_{dest} = Ex_{heat} - Ex_{work} + Ex_{mass,in} - Ex_{mass,out} . \quad (6)$$

Exergy destruction (or irreversibility) of the system can be defined as follows:

$$Ex_{dest} = \sum Ex_{in} - \sum Ex_{out} . \quad (7)$$

Generally, the exergy efficiency (also called second law and exergetic efficiency) may be presented as the ratio of total exergy output to total energy input.

$$\varepsilon = \frac{Ex_{output}}{E_{input}} . \quad (8)$$

In the considered plant, there is no environmental discharge. Slag washing water is completely returned to slag washing water pool. The power plant operates on a liquid-dominated and low-temperature resource and slag washing water remains as a liquid throughout the plant. The temperature of slag washing water entering the plant is 90 °C (i.e., $t_5 = 90^\circ\text{C}$) with a mass flow rate $m_5 = 100$ kg/s, and pressure of slag washing water is 500 kPa (i.e., $p_5 = 500$ kPa) at the entrance of evaporator. Slag washing water leaves the evaporator at 60 °C (i.e., $t_6 = 60^\circ\text{C}$).

Based on the Rankine cycle, the organic working fluid circulates in a closed loop. Working fluid enters the pump as saturated liquid at 10 °C ($t_1 = 10^\circ\text{C}$) and is pumped to 1 MPa ($p_2 = 1$ MPa), which is the evaporator pressure. The isentropic efficiency of the pump is assumed to be 75%. The organic working fluid enters the evaporator with 1 MPa ($p_2 = 1$ MPa) and leaves after it is evaporated and superheated to 90 °C ($t_3 = 90^\circ\text{C}$). The superheated organic working fluid passes through the turbine. The isentropic efficiency of the turbine is assumed to be 85%. After the organic working fluid expands in the turbine, it passes through the water-cooled condenser. It leaves the water-cooled condenser as saturated liquid at 10 °C ($t_1 = 10^\circ\text{C}$). The cooling water enters the water-cooled condenser at 7 °C ($t_7 = 7^\circ\text{C}$) and leaves at 15 °C ($t_8 = 15^\circ\text{C}$).

The binary slag washing water power plant system has been divided into four subsystems. Mass, energy, and exergy equations and efficiencies

have been defined for the evaporator as:

$$\begin{aligned}
 m_2 &= m_3 = m_{wf} , \\
 m_5 &= m_6 = m_{sww} , \\
 m_{sww} (h_5 - h_6) &= m_{wf} (h_3 - h_2) , \\
 Ex_{dest} &= (Ex_2 + Ex_5) - (Ex_3 + Ex_6) , \\
 \varepsilon &= \frac{Ex_3 - Ex_2}{Ex_5 - Ex_6} ,
 \end{aligned} \tag{9}$$

where m is the mass flow rate and the subscripts wf and sww stand for the working fluid and slag washing water, respectively.

Then, mass, energy, and exergy equations and efficiencies of the turbine can be expressed by

$$\begin{aligned}
 m_3 &= m_4 = m_{wf} , \\
 W_{turbine} &= m_{wf} (h_3 - h_4) , \\
 Ex_{dest} &= (Ex_3 - Ex_4) - W_{turbine} , \\
 \varepsilon &= \frac{W_{turbine}}{Ex_3 - Ex_4} .
 \end{aligned} \tag{10}$$

Mass, energy, and exergy equations and efficiencies of the pump are defined similarly

$$\begin{aligned}
 m_1 &= m_2 = m_{wf} , \\
 W_{pump} &= m_{wf} (h_2 - h_1) , \\
 Ex_{dest} &= W_{pump} - (Ex_2 - Ex_1) , \\
 \varepsilon &= \frac{Ex_2 - Ex_1}{W_{pump}} .
 \end{aligned} \tag{11}$$

For the condenser, the mass, energy, and exergy equations and efficiencies are as follows

$$\begin{aligned}
 m_4 &= m_1 = m_{wf} , \\
 m_7 &= m_8 = m_{cw} , \\
 m_w (h_8 - h_7) &= m_{wf} (h_4 - h_1) , \\
 Ex_{dest} &= (Ex_4 + Ex_7) - (Ex_1 + Ex_8) , \\
 \varepsilon &= \frac{Ex_8 - Ex_7}{Ex_4 - Ex_1} ,
 \end{aligned} \tag{12}$$

where m is the mass flow rate and the subscripts w stands for the cool water. Here, the overall exergy efficiency of the entire cycle may be written

as

$$\varepsilon_{cyc} = \frac{W_{turbine} - W_{pump}}{m_{wf} [h_1 - h_2 - T_0 (s_1 - s_2)]}. \quad (13)$$

3 Results and discussion

In this section, we studied the effect of different organic working fluids on the performance of binary slag washing water power plants. Under the same input conditions, mass, energy, and exergy balance equations were solved to validate the computations.

Selection of the organic working fluid affects the performance of the binary slag washing water power plant to a great extent. For the purpose of this investigation, three typical organic fluids were selected and analyzed as working fluid in the binary slag washing water power plant given in Fig. 1. These organic fluids were selected and analyzed because they are fluids which enable to satisfy operating conditions of studied power plant. Critical pressure for all selected working fluids is higher than 1 MPa and only R143a has critical temperature lower than 90 °C for the safety of the system. As a result of above reasons, the environmental, thermophysical, and safety properties of selected organic fluids are given in Tab. 1.

Table 1: Physical, safety, and environmental data of investigated 3 typical organic fluids.

Name	Safety	Ozone depletion potential	Freezing point, K	Boiling point, K	Critical temperature, K	Critical pressure, kPa	Fluid type
R227ea	–	0	146.35	256.81	374.90	2925.0	dry
R143a	A2	0	161.34	225.91	345.86	3761.0	wet
R290	A3	0	85.53	231.04	369.89	4251.1	wet

In Tabs. 2–4, the exergy rates of all organic fluids were calculated for each state. Note that state numbers refer to Fig. 1 and state 0, 0' and 0'' indicate the restricted reference state for the slag washing water, the cooling water, and the organic working fluid, respectively. In this investigation, the temperature and pressure of restricted dead state were taken to be $t_0 = 5\text{ °C}$ and $p_0 = 0.1\text{ MPa}$ (101.25 kPa). Engineering Equation Solver (EES) commercial software package was used to calculate the properties of

organic working fluids, slag washing water, and cooling water.

Using the values given in Tabs. 2–4, the exergy destruction for all organic fluids used in binary slag washing water power plant was determined. The exergy destructions for the various components of the plant were shown in Fig. 2. The results showed that higher exergy destruction occurs in the evaporator. Other subsystems of the plant show lower exergy destruction than the evaporator. Therefore, the evaporator plays a key role on the performance of the plant.

Table 2: Calculated exergy rates and thermodynamics properties for R227ea. State numbers refer to Fig. 1.

State no.	Working fluid	Phase	T , K	p , MPa	h , kJ/kg	s , kJ/kg K	m , kg/s	Specific exergy, kJ/kg	Exergy rate, kW
0	Slag washing water	Reference state	278	0.101	20.49	0.07398	–	–	–
0'	Cooling water	Reference state	278	0.101	20.49	0.07398	–	–	–
0''	R227ea	Reference state	278	0.101	330.2	1.507	–	–	–
1	R227ea	Saturated liquid	283	0.279	211.1	1.04	71.11	10.73	762.7
2	R227ea	Liquid	283.3	1.0	211.7	1.04	71.11	11.34	805.4
3	R227ea	Superheated vapor	358	1.0	388.6	1.589	71.11	35.6	2531.8
4	R227ea	Superheated vapor	332.9	0.279	373.6	1.589	71.11	20.6	1465.2
5	Slag washing water	Liquid	363	0.5	377.4	1.193	100	45.82	4582
6	Slag washing water	Liquid	333	0.5	251.6	0.831	100	20.66	2066
7	Cooling water	Liquid	280	0.5	29.9	0.106	343.9	0.51	174.9
8	Cooling water	Liquid	288	0.5	63.5	0.224	343.9	1.304	448.6

The exergy destruction in evaporator is a large portion of overall exergy

Table 3: Calculated exergy rates and thermodynamics properties for R143a. State numbers refer to Fig. 1.

State no.	Working fluid	Phase	T , K	p , MPa	h , kJ/kg	s , kJ/kg K	m , kg/s	Specific exergy, kJ/kg	Exergy rate, kW
0	Slag washing water	Reference state	278	0.101	20.49	0.07398	–	–	–
0'	Cooling water	Reference state	278	0.101	20.49	0.07398	–	–	–
0''	R143a	Reference state	278	0.101	405.89	1.921	–	–	–
1	R143a	Saturated liquid	283	0.837	215.2	1.054	47.56	50.34	2394
2	R143a	Liquid	283.1	1.0	215.4	1.054	47.56	50.55	2403.5
3	R143a	Superheated vapor	358	1.0	479.9	1.936	47.56	69.84	3321.6
4	R143a	Superheated vapor	356.1	0.837	474	1.936	47.56	63.94	3041
5	Slag washing water	Liquid	363	0.5	377.4	1.193	100	45.82	4582
6	Slag washing water	Liquid	333	0.5	251.6	0.831	100	20.66	2066
7	Cooling water	Liquid	280	0.5	29.9	0.106	366.3	0.51	186.2
8	Cooling water	Liquid	288	0.5	63.5	0.224	366.3	1.304	477.8

destruction of the cycle (Fig. 2). Revealing minimum exergy destruction in evaporator for the fluid such as R227ea results in minimum exergy destruction percentage for the overall overall system. It can be also shown in Fig. 3 that R227ea gives rise to low exergy losses relatively. It is expected that R227ea has the best performance, due to its minimum exergy destruction.

It is important to note that net work affects directly performance of the binary cycle. Net work is defined as the difference between work input and work output. The net work between work produced in the turbine and work consumed in the pump is different in this cycle. The net work rate

Table 4: Calculated exergy rates and thermodynamics properties for R290. State numbers refer to Fig. 1.

State no.	Working fluid	Phase	T , K	p , MPa	h , kJ/kg	s , kJ/kg K	m , kg/s	Specific exergy, kJ/kg	Exergy rate, kW
0	Slag washing water	Reference state	278	0.101	20.49	0.07398	–	–	–
0'	Cooling water	Reference state	278	0.101	20.49	0.07398	–	–	–
0''	R290	Reference state	278	0.101	597.23	2.73	–	–	–
1	R290	Saturated liquid	283	0.637	225.6	1.091	24.89	84.01	2091.1
2	R290	Liquid	283.2	1.0	226.3	1.091	24.89	84.71	2108.5
3	R290	Superheated vapor	358	1.0	731.8	2.74	24.89	131.79	3280.3
4	R290	Superheated vapor	345.4	0.637	704	2.74	24.89	103.99	2588.3
5	Slag washing water	Liquid	363	0.5	377.4	1.193	100	45.82	4582
6	Slag washing water	Liquid	333	0.5	251.6	0.831	100	20.66	2066
7	Cooling water	Liquid	280	0.5	29.9	0.106	354.4	0.51	180.2
8	Cooling water	Liquid	288	0.5	63.5	0.224	354.4	1.304	462.3

of investigated organic fluids is shown in Fig. 4. As a result of analysis, R227ea features the maximum net work rate and R143a has the minimum net work rate.

First and second law efficiencies of the overall cycle were calculated as shown in Fig. 5. We can find that R227ea exhibits the best first and second law efficiencies. It has 8.14% first law efficiency and 40.69% second law efficiency. On the other hand, R143a shows the worst first law efficiency 2.16% and second law efficiency 10.77%.

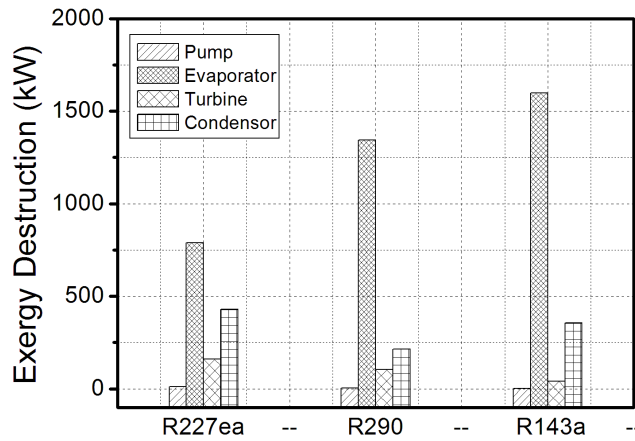


Figure 2: Exergy destruction of screened organic fluids at various components of the plants.

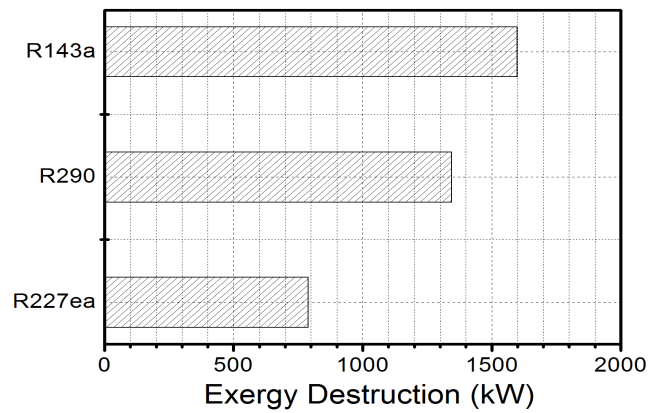


Figure 3: Exergy destruction of the system with different organic fluids.

4 Conclusions

1. In the considered slag washing water binary power plant, energy (first law) efficiencies are obtained in the range of 2–8%, and exergy (second law) efficiencies are gained in the range of 10–40%. The considered

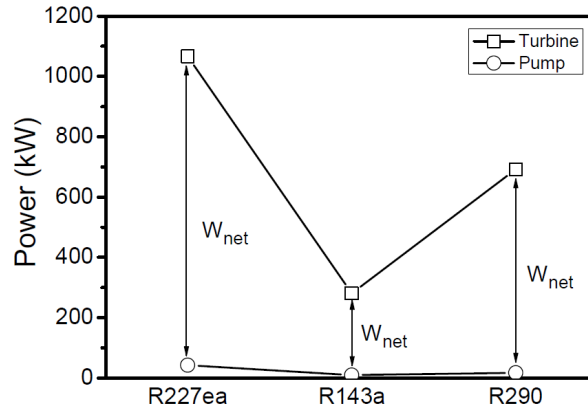


Figure 4: Net work rates of investigated organic fluids.

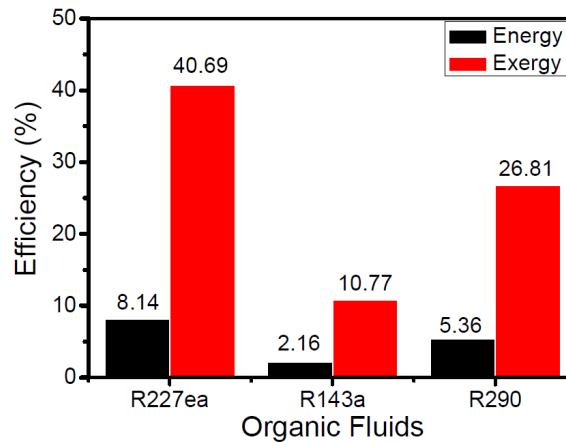


Figure 5: Energy and exergy efficiency of the investigated organic fluids.

slag washing water binary power plant which uses low-temperature slag washing water resource as a heat source exhibits higher exergy efficiency than energy efficiency.

2. According to the analysis, it is observed that selection of the organic fluids influence the system performance. Dry type organic fluid R227ea among the screened organic fluids demonstrates higher first and second law efficiencies than wet type organic fluids R290 and R143a. As a result, dry type organic fluids should be preferred as

working fluid in the binary power cycle, which produces electricity from low-temperature slag washing water resource.

3. It has been determined that the evaporator is of great importance in terms of system performance. As the exergy destruction that has been caused by the refrigerants in the evaporator increase, energy and exergy efficiencies decrease. Organic fluid R227ea which caused the minimum exergy destruction in the evaporator has exhibited the highest energy and exergy efficiencies.
4. In contrast, R143a which caused the maximum exergy destruction in the evaporator has shown the lowest energy and exergy efficiencies. Therefore, exergy destruction in the evaporator should be taken into consideration during the selection of the working fluid.

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