Thermodynamic Performance Analysis of Organic Rankine Cycle with Turbine Bleeding Under Condition of Critical Bleeding Fraction

Kyoung Hoon Kim, and Sang Hee Park

Abstract - This work presents a thermodynamic performance analysis of organic Rankine cycle (ORC) with turbine bleeding for recovery of finite thermal energy. Effects of the bleeding pressure and selection of working fluid are theoretically investigated on the system performance under the conditions of the critical bleeding fraction. The results show that the critical bleeding fraction increases with increasing bleeding pressure or the critical temperature of working fluid. The thermodynamic performance of the system is significantly influenced by the bleeding pressure or selection of working fluid.

Keywords - organic Rankine cycle (ORC), regeneration, turbine bleeding, critical bleeding fraction.

I. Introduction

THE accelerated consumption of fossil fuels has caused many serious environmental problems such as air pollution, global warming, ozone layer depletion and acid rain, but Rankine cycle driven by fossil fuels is still the dominant power supply method. How to effectively utilize low and medium temperature energy which is vast but undeveloped is one of the solutions to alleviate the energy shortage and environmental pollution problems. However, many problems are encountered when using water as the working fluid for steam Rankine cycle [1].

The organic Rankine cycle (ORC) applies the principle of the steam Rankine cycle, but uses organic working fluids with low boiling points to recover heat from lower temperature heat sources [2]. The basic ORC consists of a pump which pressurizes the working fluid and transports it to the evaporator. In the evaporator, the working fluid is heated to the point of saturated or superheated vapor. Next, the working fluid expands through an expander and produces mechanical work. This shaft power can then be converted to electricity by the generator. The superheated working fluid at the outlet of the expander is condensed to saturated liquid in the condenser. The liquid working fluid is again pressurized by the pump, closing the cycle. The heat sink and heat source are a finite thermal reservoir and are indicated respectively as line [3].

During the past decades the ORC have attracted much attention as they are proven to be the most feasible methods to achieve high efficiency in converting the low-grade thermal energy to more useful forms of energy. Schuster et al. [4] investigated numerous running applications such as geothermal power plants and waste heat recovery or micro-CHP. Heberle and Brueggemann [5] investigate the CHP generation for geothermal resources with series and parallel circuits of an ORC. Dai et al. [8] examined the effects of the thermodynamic parameters on the ORC performance, and the parameters for each working fluid are optimized with exergy efficiency. Tchanche et al. [9] comparatively investigated the performances as well as thermodynamic and environmental properties of the fluids for use in low-grade solar ORC systems.

Gao et al. [10] carried out the analysis of a supercritical organic Rankine cycle system driven by exhaust heat using 18 organic working fluids. Dai et al. [11] proposed a combined power and refrigeration cycle, which combines an organic Rankine cycle and an ejector refrigeration cycle. Li et al. [12] performed an exergoeconomic analysis and optimization of a condenser for a binary mixture in ORC systems. Walraven et al [13] investigated comparatively the performance of ORC and Kalina cycles. Wang et al. [14] proposed a theoretical model based on an ideal ORC to analyze the influence of working fluid properties on the thermal efficiency.

Kim and Perez-Blanco [15] reported a thermodynamic analysis of cogeneration of power and refrigeration activated by low- grade sensible energy.

ORCs with turbine bleeding which is coupled to a direct contact heat exchanger are typically designated as regenerative ORCs and these cycles closely resemble the ORC with recuperator. Mago et al. [16] presented an analysis of a regenerative ORC and compared this with the basic ORC. Their results show that regenerative ORC shave a higher thermal efficiency and lower irreversibilities. Desai and Bandyohyay [17] investigated on ORC incorporating both regeneration and turbine bleeding. Meinel et al. [18] presented simulations of a two-stage ORC concept with internal recovery.

This work presents a thermodynamic performance analysis for a regenerative ORC with turbine bleeding to convert low temperature heat source to useful energy for various working fluids. Effects of the turbine bleeding pressure and the selection of working fluid are theoretically investigated on the system performance including the mass flow rate of working fluid, heat transfer rate, critical bleeding fraction, net power production and thermal efficiency of the system.

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II. System Analysis

The schematic diagram of the system is shown in Fig. 1. The system consists of pump, heat exchanger, turbine, condenser, and feed heater. A low grade heat source is supplied to the system as sensible heat energy.

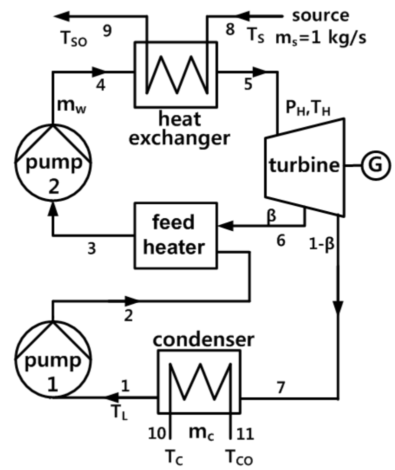

Fig. 1. Schematic diagram of the system.

The working fluid leaves the condenser as saturated liquid at T_L (state 1) where the corresponding saturation pressure P_L is the low pressure of the system. The fluid is compressed with the pump 1 to P_B which is the pressure of turbine bleeding (point 2) and is mixed in the feed heater with the working fluid from the turbine bleeding (state 6). The working fluid leaving the feed heater which is assumed to be pure liquid (state 3) is compressed to the turbine inlet pressure P_H (state 4) with pump 2. The fluid is then heated in the heat exchanger to the turbine inlet temperature T_H (state 5) while the heat source is supplied at temperature T_S (state 8) and is cooled to T_{SO} (state 9) after heating the working fluid in the heat exchanger. Among 1 kg of the vapor at turbine inlet, vapor of β kg is expanded to the turbine bleeding pressure P_B and is bleeded, while the remained (1-β) kg of vapor is fully expanded to the condensation pressure P_L (state 7). The coolant enters the condenser at T_C and leaves the condenser at T_{CO} after condensates the working fluid.

For the simplicity of simulations, it is assumed in this study as follows: 1) The working fluid at turbine inlet is pure vapor. 2) The working fluid leaving the feed heater is saturated liquid. The fraction of turbine bleeding which leads to the working fluid as saturated liquid is defined as the critical bleeding fraction β. 3) The isentropic efficiencies of pump and turbine are maintained at constant values of η_p and η_t, respectively. 4) The minimum temperature difference between hot and cold streams in the source heat exchanger or condenser is the prescribed value of pinch point, ΔT_{pp}.

The mass flow rates of working fluid at heat exchanger and coolant at condenser are indicated as m_s and m_c, respectively, and can be evaluated as

$$m_w = \frac{c_{ps}(T_s - T_{so})}{h_5 - h_4} \tag{1}$$

$$m_c = \frac{m_w(1-\beta)(h_7 - h_1)}{c_{pc}(T_{co} - T_c)} \tag{2}$$

where subscripts w and c denote the working fluid and the coolant, respectively, and m the mass flow rate, T the temperature, h the specific enthalpy, and c_{ps} and c_{pc} the isobaric specific heat of source and coolant, respectively.

The critical bleeding fraction β, can be determined from the condition of saturate liquid at state 3 as follows.

$$\beta = \frac{h_f(P_B) - h_2}{h_6 - h_2} \tag{3}$$

where h_f denotes the saturated liquid at a given pressure.

Then the heat input Q_{in}, heat rejection Q_{out}, pump power W_p, turbine power W_t, and net power production W_{net} can be obtained as

$$Q_{in} = m_w(h_5 - h_4) \tag{4}$$

$$Q_{out} = m_w(1-\beta)(h_7 - h_1) \tag{5}$$

$$W_p = m_w(1-\beta)(h_2 - h_1) + m_w(h_4 - h_3) \tag{6}$$

$$W_t = m_w(1-\beta)(h_5 - h_7) + m_w\beta(h_5 - h_6) \tag{7}$$

$$W_{net} = W_t - W_p \tag{8}$$

Eight fluids of R134a, R152a, propane, isobutane, butane, R245fa, R123, and isopentane are considered. In this work the thermodynamic properties of the working fluids are evaluated using the Patel-Teja equation of state [19-20]. The basic thermodynamic data for the working fluids are listed in Table I [21].

TABLE I
BASIC THERMODYNAMIC DATA OF WORKING FLUIDS

Substance	M(kg/kmol)	T_{cr}(K)	P_{cr}(bar)	ω
R134a	102.031	380.00	36.90	0.239
R152a	66.051	386.60	44.99	0.263
propane	44.096	396.82	42.49	0.152
isobutane	58.123	408.14	36.48	0.177
butane	58.123	425.18	37.97	0.199
R245fa	134.048	427.20	36.40	0.372
R123	136.467	456.90	36.74	0.282
isopentane	72.150	460.43	33.81	0.228

III. Results and Discussions

In this work a thermodynamic performance analysis is carried out for a regenerative ORC with turbine bleeding under the condition of the critical bleeding fraction to convert low temperature heat source to useful energy. The basic system parameters used in the simulation for the analysis are summarized in Table II.

TABLE II
BASIC CALCULATION CONDITIONS

symbol	Parameter	data	unit
T_s	source temperature	200	°C
T_H	turbine inlet temperature	190	°C
T_c	coolant temperature	15	°C
T_L	condensing temperature	30	°C
P_H	reduced turbine inlet pressure	0.8	
T_0	ambient temperature	15	°C
ΔT_{PP}	pinch temperature difference	8	°C
η_p	isentropic efficiency of pump	0.80	
η_t	isentropic efficiency of turbine	0.80	
	source fluid	air	

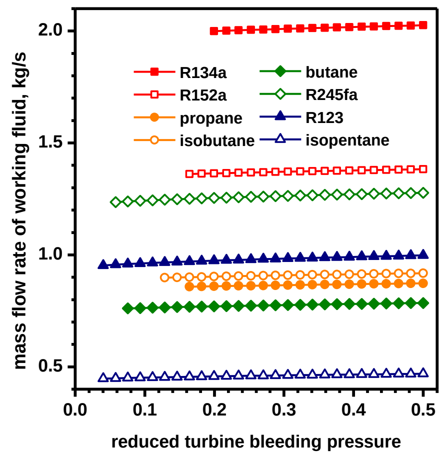

Fig. 2. Variations of mass flow rate of working fluid with reduced turbine bleeding pressure.

The mass flow rate of working fluid is plotted against the reduced turbine bleeding pressure in Fig. 2 for various working fluids. As the bleeding pressure increases for a given bleeding fraction, the mass flow rate increases slightly. It is because an increase in the bleeding pressure causes a rise in temperature or specific enthalpy of working fluid at evaporator inlet. The mass flow rate is the highest for R134a and the lowest for isopentane.

Fig. 3 demonstrates the critical bleeding fraction with respect to the reduced bleeding pressure for various working fluids. The bleeding fraction should be equal to or lower than the critical bleeding fraction for working fluid to be a liquid at the exit of the feed heater. The critical fraction increases with increasing turbine bleeding pressure. It is because as the bleeding pressure increases, the corresponding saturation temperature also increases so that it is required more bleeding flow to make the working fluid from compressed liquid to saturated liquid. It can be seen from the figure that the critical bleeding fraction increases with increasing critical temperature of working fluid.

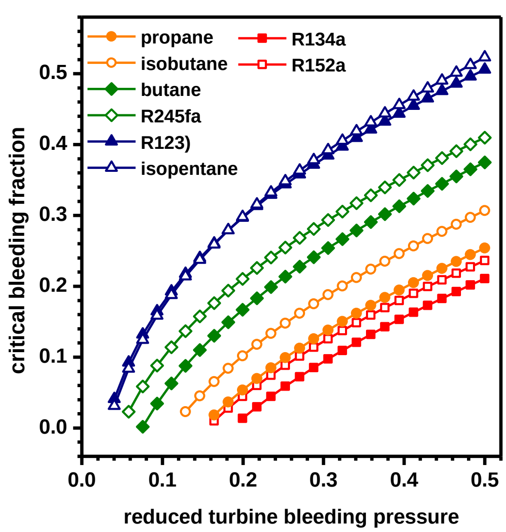

Fig. 3. Variations of critical bleeding fraction with turbine bleeding pressure.

The evaporator inlet temperature, T_4 is plotted against the reduced turbine bleeding pressure in Fig. 4 for various working fluids. It can be seen from the figure that the evaporator inlet temperature increases with increasing bleeding pressure or the critical temperature of working fluid. It is because as the turbine bleeding pressure increases, the corresponding saturation temperature at the exit of the feed heater increases. The evaporator is the highest for isopentane and the lowest for R134a.

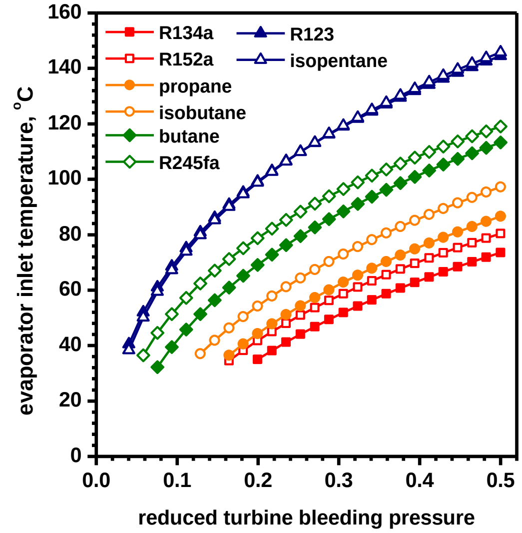

Fig. 4. Variations of anergy ratio of heat exchanger with turbine bleeding pressure.

Fig. 5 demonstrates the heat addition rate with respect to the bleeding pressure for various working fluids. The heat addition decreases with increasing turbine bleeding pressure. It is because as the bleeding pressure increases, the working fluid temperature at the evaporator inlet increases, which lowered the temperature difference between the source and working fluid. For a given turbine bleeding pressure, the heat addition rate decreases with increasing critical temperature of working fluid, since the higher the critical temperature of the working fluid is, the higher the working fluid temperature at evaporator is, as is seen in Fig. 4.

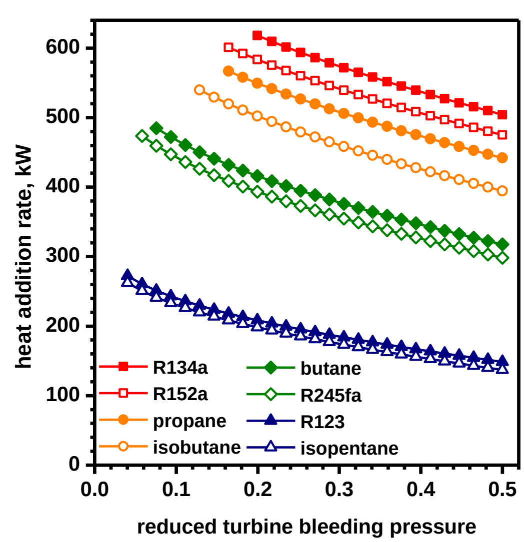

Fig. 5. Variations of anergy ratio of heat exchanger with turbine bleeding pressure.

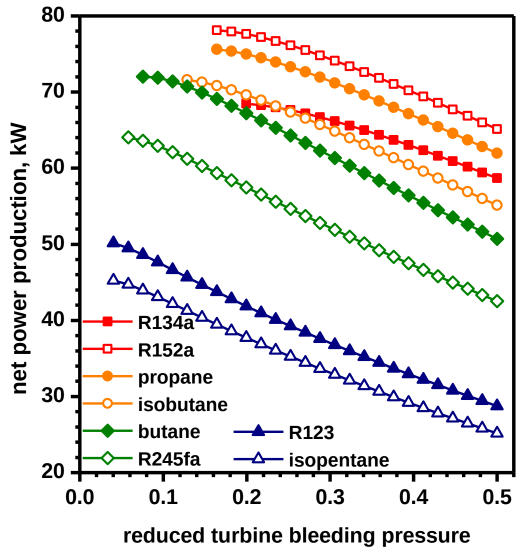

Fig. 6. Variations of anergy ratio of heat exchanger with turbine bleeding pressure.

Fig. 6 shows the net power production with respect to the bleeding pressure for various working fluids. The net power production decreases with increasing turbine bleeding pressure. It is because as the bleeding pressure increases, the mass flow rate of bleeded fluid increases as well as the temperature of bleeded fluid at the evaporator inlet increases, which lowered the power production at turbine. For a given turbine bleeding pressure, the net power production is the highest for R152a, while the lowest for isopentane.

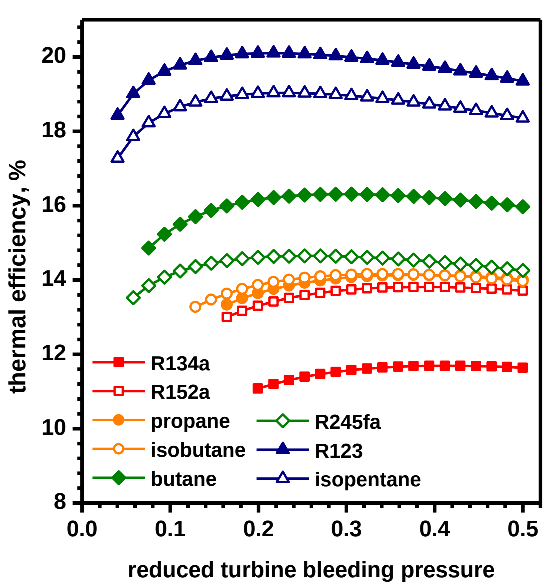

Fig. 7. Variations of anergy ratio of heat exchanger with turbine bleeding pressure.

Fig. 7 shows the thermal efficiency of the system with respect to the bleeding pressure for various working fluids. The thermal efficiency is defined as the ratio of net power production to heat addition rate to the system. As the turbine bleeding pressure increases, not only the net power production but also the heat addition rate increases. Thus, the thermal efficiency has a peak value with respect to the turbine bleeding pressure. For a given turbine bleeding pressure, the thermal efficiency is the highest for R123, while the lowest for R134a.

IV. Conclusions

In this paper, the thermodynamic performance of regenerative ORC with turbine bleeding was analyzed under the condition of critical bleeding fraction. The main results are as follows:

1) The critical bleeding fraction increases with turbine bleeding pressure, however, the heat addition rate and net power production decrease with increasing turbine bleeding pressure.
2) For a specified turbine bleeding pressure, the critical bleeding fraction increases but the heat addition rated decreases as the critical temperature of working fluid increases.
3) The thermal efficiency of the system has a peak value with respect to turbine bleeding pressure, and is the highest for R123 and the lowest for R134a.

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