Performance Analysis of a Combined Power and Ejector Refrigeration Cycle for Different Working Fluids

Kyoung Hoon Kim, Chul Ho Han, Se Woong Kim, and Hyung Jong Ko

***Abstract*—** The performance of a combined power and ejector refrigeration cycle is thermodynamically investigated for the utilization of low-temperature waste heat. Total five kinds of dry fluids are considered as working fluid of the cycle with a source fluid of water at 150^{o}C. Special attention is paid to the effects of turbine inlet and outlet pressure on the cycle performance including the thermal efficiency of the cycle. The results show that the thermal efficiency increases with turbine inlet and out pressure for the considered pressure range and working fluids. Fluid with higher critical temperature gives higher entrainment ratio, lower specific net work, and higher thermal efficiency.

***Keywords*—**cogeneration, ejector refrigeration cycle, organic Rankine cycle, thermal efficiency, working fluids.

I. Introduction

DUE to the lack of effective methods of recovery, low-temperature waste heat from industrial processes is merely discharged and the discharged waste heat becomes one of the causes of environmental problem [1]. The organic Rankine cycle (ORC) has been considered as one of the promising technologies for the conversion of low-temperature waste heat into useful forms of energy. There have been an increasing number of researches on the recovery of low-temperature waste heat [2]-[4].

The selection of working fluid which matches with the available heat source and temperature range is important. Saleh et al. [5] performed a thermodynamic screening of 31 pure working fluids for the temperature range typical to geothermal power plants. Mago et al. [6] presented an analysis of regenerative ORCs using dry organic fluids. In a study of ORC in solid biomass power and heat plants, Drescher and Brueggemann [7] proposed a method to find suitable thermodynamic fluids for ORCs in biomass plants and found that the family of alkylbenzenes showed the highest efficiency. Heberle and Brueggemann [8] investigated the combined heat and power generation for geothermal resources with an ORC and suggested an exergy-based fluid selection method.

Ejector refrigeration cycle (ERC) has some advantages in that it can be driven by low-grade energy sources and is simple since the ejectors have no moving parts [9]. ERC can be combined with various power cycles for the cogeneration of power and refrigeration. Dai et al. [10] proposed a novel combined cycle, in which a turbine is added between boiler and ejector of ERC. Exergy analysis, parametric analysis, and parameter optimization of exergy efficiency are conducted to the combined cycle using R123 as working fluid. This cycle was also investigated by Zheng and Weng[11] and Ko and Kim[12] for the working fluid of R245fa. A modified version of the combined cycle of [10], in which only a part of vapor was extracted from the turbine to the ejector, was studied by Wang et al. [13] for the same fluid and by Habibzadeh et al. [14] for several working fluids. Li et al. [15] proposed an organic Rankine cycle with ejector (EORC) for the purpose of increasing the power output capacity and its efficiency. Soroureddin et al. [16] investigated the combined ORC and ERC driven by waste heat from the gas turbine-modular helium reactor (GT-MHR) in three different configurations.

In this study a thermodynamic performance analysis of a combine power and ejector refrigeration cycle which has been studied by [10]-[12] is carried out for the utilization of low-temperature waste heat. Effects of turbine inlet and outlet pressure on the system performance including the thermal efficiency of the cycle are parametrically investigated for different working fluids.

II. System Analysis

A schematic diagram of the combined power and ejector refrigeration cycle is shown in Fig. 1. The combined cycle can be divided into two sub-cycles. The processes 1-2-3-4-5-6-1 comprise a power sub-cycle and the processes 5-7-8-9-3-4-5 comprise a refrigeration sub-cycle. Two sub-cycles share an ejector and a condenser. The primary flow in the ejector comes from the turbine and induces the secondary flow from the evaporator. When the pump is connected to the turbine, the entire system is driven by the sensible heat of a low-temperature

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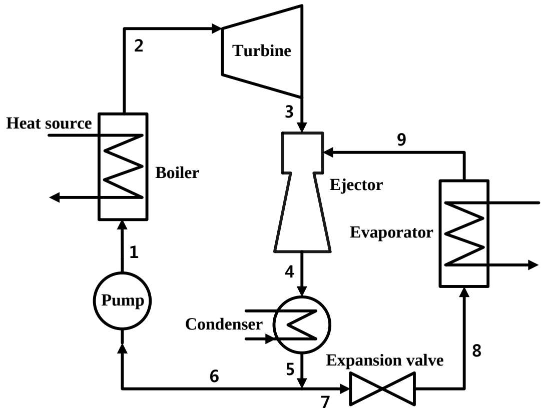

Fig. 1 Schematic diagram of the system.

heat source. Heat is rejected to the coolant at the condenser, while some heat is removed from the space surrounding the evaporator. Both the source fluid and the coolant are considered as water. Five kinds of organic fluids are considered for the working fluid of the cycle, which can be listed in the order of descending critical temperature as normal pentane (nC_5H_{12}), isopentane (iC_5H_{12}), R123 ($CHCl_2CF_3$), R245fa ($CHF_2CH_2CF_3$), and isobutane (iC_4H_{10}). All of the considered fluids are categorized as dry fluids and their thermodynamic properties are calculated by the Patel-Teja equation of state [17], [18]. The basic data of the working fluids needed when applying the Patel-Teja equation are shown in TABLE 1. Here, M, T_{cr}, P_{cr} and ω are molecular weight, critical temperature, critical pressure, and acentric factor, respectively [19].

In order to investigate the thermodynamic performance of the combined cycle some simplifications are used [10, 12]: The system operates in a steady state. Pressure drop and heat loss in the system are negligible. The working fluid enters the turbine as superheated vapor, and leaves the condenser and evaporator as saturated liquid and saturated vapor, respectively. The minimum temperature difference between the hot and cold streams in the boiler and condenser is held at a prescribed value of pinch point temperature difference. The pump and turbine have constant isentropic efficiency. The flow in the ejector is one-dimensional and the mixing of primary and secondary flows occurs at constant pressure. In addition the effects of irreversibility at the nozzle, mixing, and diffuser sections of the ejector can be taken into account by using their efficiencies. The process in the expansion valve is isenthalpic.

Using these assumptions and referring to Fig. 1 the thermodynamic states at 1 to 9 can be determined for given turbine inlet pressure and temperature, turbine outlet pressure, and condenser and evaporator temperature. In the procedure the exit state 4 and entrainment ratio of the ejector have to be determined iteratively from the balance equations of mass, momentum and energy, and the thermodynamic equation of states [10].

It is desirable to circulate more working fluid and less coolant fluid for a given mass flow rate of source fluid, unless the pinch point condition is violated. For a given mass flow rate of source

TABLE I
BASIC DATA FOR THE WORKING FLUIDS

Substance	M(kg/kmol)	T_{cr}(K)	P_{cr}(bar)	ω
normal pentane	72.150	469.65	33.69	0.249
isopentane	72.150	462.43	33.81	0.228
R123	136.467	456.90	36.74	0.282
R245fa	134.048	427.20	36.40	0.3724
isobutane	58.123	408.14	36.48	0.177

fluid (m_s), the mass flow rate of working fluid of power cycle (m_t) can be determined from the energy balance and pinch point condition at the boiler. Hence the mass flow ratio $r_{t/s}$ is written as

$$r_{t/s} = m_t / m_s = c_{ps}\left(T_{s,i} - T_{s,e}\right) / (h_2 - h_1) \tag{1}$$

$$\min(T_s - T_{wf}) = \Delta T_{PP} \tag{2}$$

where c_{ps} is the isobaric specific heat of the source fluid and h is the specific enthalpy of the working fluid. T_s and T_{wf} mean the temperature of source fluid and working fluid. The subscripts i and e refer to the inlet and exhaust of the source fluid, and ΔT_{PP} is the pinch point temperature difference. The mass flow rate of working fluid of refrigeration cycle (m_e) is determined by the entrainment ratio of ejector ($r_{e/t} = m_e/m_t$) which is obtained from the coupled ejector equations. The mass flow rate in the condenser is equal to the sum of those in the turbine and evaporator, that is,

$$m_{cd} = m_t + m_e = m_t(1 + r_{e/t}) \tag{3}$$

The coolant mass flow rate (m_c) is determined from the energy balance and pinch point condition at the condenser.

The rates of heat input, net work production and refrigeration output can be calculated from

$$Q_{in} = m_t\left(h_2 - h_1\right), \tag{4}$$

$$W_{net} = W_t - W_p = m_t\left[\left(h_2 - h_3\right) - \left(h_1 - h_6\right)\right], \tag{5}$$

$$Q_e = m_e\left(h_9 - h_8\right). \tag{6}$$

Among other variables estimating the effectiveness of the waste heat recovery, the net work and refrigeration per unit mass of source fluid are important. These are calculated as

$$w_{net/s} = w_{t/s} - w_{p/s} = r_{t/s}\left[\left(h_2 - h_3\right) - \left(h_1 - h_6\right)\right], \tag{7}$$

$$q_{e/s} = r_{e/t} r_{t/s}\left(h_9 - h_8\right), \tag{8}$$

Respectively. Finally the thermal efficiency of the system is defined as the useful energy output divided by the total energy input, and given by

$$\eta_{th} = (W_{net} + Q_e) / Q_{in}. \tag{9}$$

Here the quality difference between work and heat is not considered.

III. Results and Discussions

The thermodynamic performance of a combined power and ejector refrigeration cycle driven by the sensible heat of low-temperature heat source is investigated for different working fluids. Water is considered as source fluid with inlet temperature of 150°C. Since the purpose of the investigation is a search for an effective method of waste heat recovery, performance of the system is estimated on a unit mass base of source fluid. Total five kinds of dry organic fluids are considered as working fluid of the combined cycle; normal pentane (nC_5H_{12}), isopentane (iC_5H_{12}), R123 ($CHCl_2CF_3$), R245fa ($CHF_2CH_2CF_3$), and isobutane (iC_4H_{10}). The inlet and outlet pressure of turbine are varied from 5 to 30 bar and from 3 to 10 bar, respectively, while the turbine inlet and condenser temperature are fixed at 130°C and 25°C. Other basic data for analysis are summarized as follows. Coolant temperature: 15°C, environment temperature: 15°C, evaporator temperature: -20°C, temperature of cooled space: -5°C, pinch point temperature difference: 5°C, isentropic efficiency of pump: 0.7, isentropic efficiency of turbine: 0.85, nozzle efficiency: 0.95, mixing efficiency: 0.95, diffuser efficiency: 0.95.

The combined cycle cogenerates power and refrigeration. The power generation performance is mainly influenced by the turbine inlet conditions, while the dependence of refrigeration performance on system variables is rather complicated. For example, the mass flow ratio of refrigeration cycle to power cycle is determined by the entrainment of the ejector, which is affected by the inlet and outlet conditions of ejector. If the turbine outlet pressure (TOP) is raised, then more fluid is entrained from the evaporator owing to an increased thermal energy of entrainment. The counter effect raising TOP is a decrease of turbine work due to the decrease of enthalpy drop. In this study the system performance is investigated by varying the turbine inlet pressure (TIP) and TOP. The other parameters such as the turbine inlet temperature (TIT), condenser temperature, and evaporator temperature are held constant.

The simulation results for varying TIP in the range of 5 to 30 bar are presented in Fig. 2 to Fig. 5. But the range of TIP is restricted such that the fluid must enter the turbine at a superheated vapor state. For TIT of 130°C, it is narrower as the critical temperature of the fluid increases. The TOP is fixed at 6 bar, which is comparatively higher than that of pure power cycle.

Fig. 2 shows the variation of entrainment ratio of ejector ($r_{e/t}$) with respect to TIP for various working fluids. The entrainment ratio shows an almost linearly decreasing behavior on TIP for all fluids, although the slope is not steep. This is because an increase of TIP results in a decrease of TOP for the fixed TIT and the low TOP causes a reduction of thermal energy of the primary flow. The entrainment ratio of working fluid with higher critical temperature is relatively higher and isobutane has remarkably small value. However this result is only for TOP of 6 bar; The entrainment ratio is dependent on TOP. The refrigeration performance is largely affected by the entrainment ratio of ejector because the amount of heat removal by the evaporator is proportional to the mass flow rate in the evaporator.

Net work per unit mass of source fluid versus TIP is plotted for various working fluids in Fig. 3. Because the TOP is 6 bar, net work diminishes to zero as the TIP approaches 6 bar. Hereafter an expression of ‘specific’ will be used to mean the ‘per unit mass of source fluid.’ Specific net work of each fluid first increases to a maximum and then decreases as the TIP increases. This behavior is a result of combined effect of TIP which increases the enthalpy drop but decreases the mass flow rate. For the same TIP and TOP, specific net work of working fluid with higher critical temperature is relatively smaller.

Specific refrigeration versus TIP is plotted for various working fluids in Fig. 4. For each fluid, specific refrigeration decreases almost linearly with the increase of TIP. The reason is that the mass flow rate of evaporator decreases with TIP for a

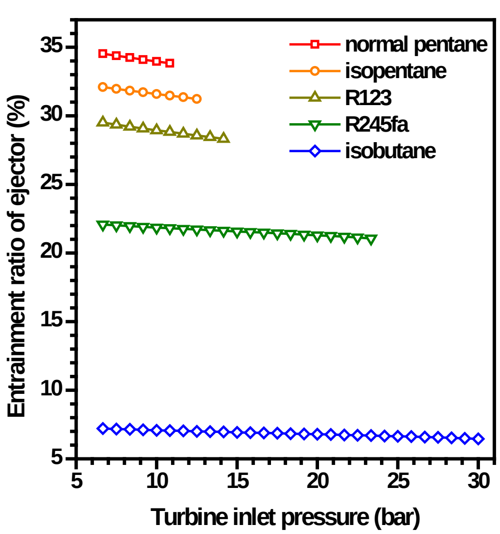

Fig. 2 Variation of entrainment ratio of ejector with respect to turbine inlet pressure for various working fluids.

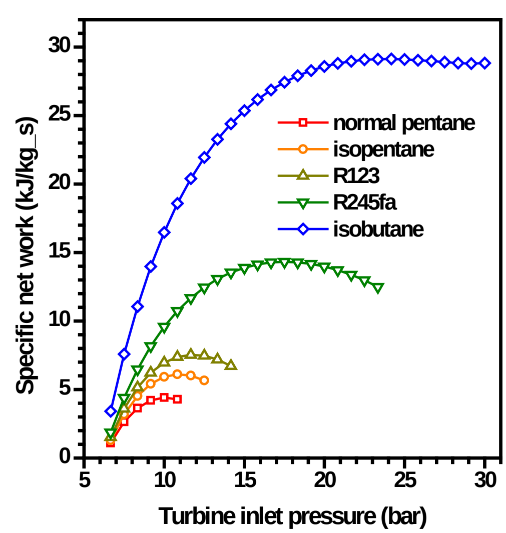

Fig. 3 Net work per unit mass of source fluid versus turbine inlet pressure for various working fluids.

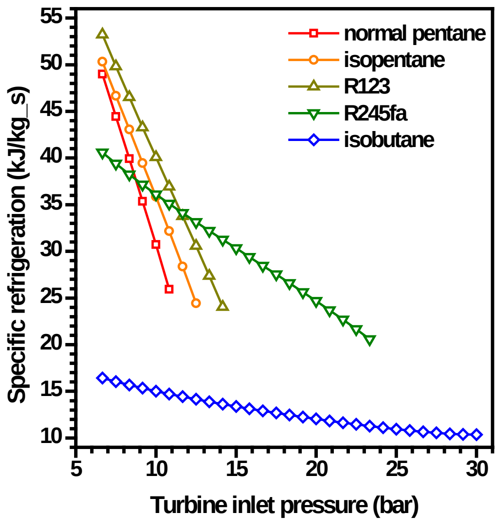

Fig. 4 Refrigeration per unit mass of source fluid versus turbine inlet pressure for various working fluids.

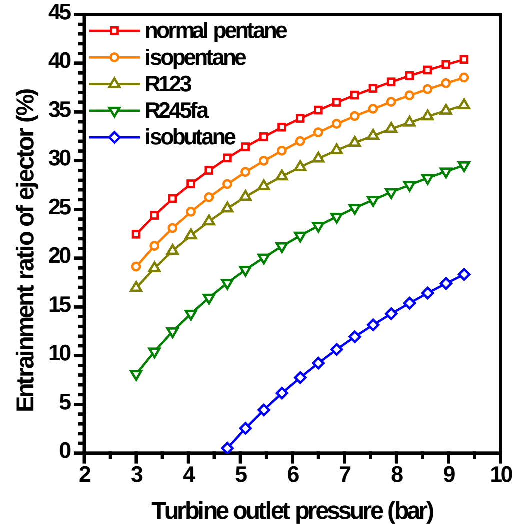

Fig. 6 Variation of entrainment ratio of ejector with respect to turbine outlet pressure for various working fluids.

given source fluid. The mass flow ratio of evaporator to source fluid ($r_{e/s}$) is equal to the product of entrainment of ejector ($r_{e/t}$) and mass flow ratio of turbine to source fluid ($r_{t/s}$). Both ratios are lower at higher TIPs. The slope of the change of specific refrigeration with respect to TIP is much steeper for normal pentane, isopentane, and R123 than R245fa and isobutane.

Fig. 5 shows that thermal efficiency of the combined cycle is monotonically increasing with TIP within the range considered for all fluids. This behavior is a result of combined effects of net work, refrigeration capacity, and heat input in the boiler. It is worth to note that the temperature difference between the hot and cold streams in the boiler is kept equal to the pinch point temperature difference. Among the fluids considered normal pentane and isobutene give maximum and minimum efficiency respectively. On the whole, fluid with high critical temperature results in a high thermal efficiency.

The results of performance simulation for varying TOP in the range of 3 to 10 bar are shown in Fig. 6 to Fig. 9. The TIP and TIT are fixed at 10 bar and 130^{o}C. Unfortunately under this turbine inlet conditions, the TOP less than 4.7 bar is not able to entrain the secondary flow to the ejector for isobutane.

Fig. 6 shows that the entrainment ratio of ejector ($r_{e/t}$) monotonically increases with the increase of TIP for all working fluids under consideration. This is readily expected since the thermal energy of the primary flow needed to entrain the secondary flow increases with TOP. Equally to the dependence on TIP, the entrainment ratio of fluid with higher critical temperature is relatively higher for all values of TOP.

Fig. 7 is a plot of specific net work versus TOP for various working fluids. Since the TIP is kept at 10 bar, net work diminishes to zero as the TOP approaches 10 bar. Contrary to the entrainment ratio of ejector, the specific net work of each

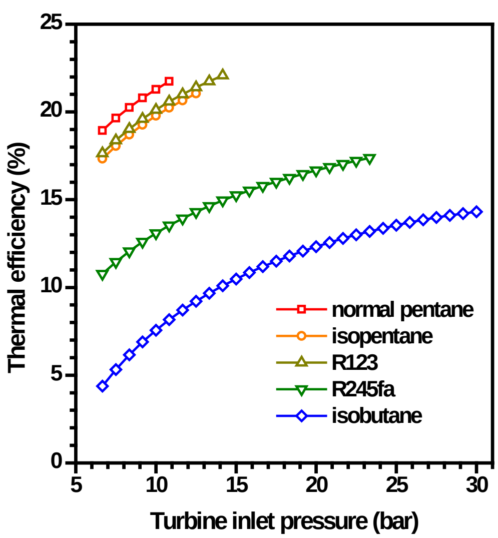

Fig. 5 Dependence of thermal efficiency on turbine inlet pressure for various working fluids.

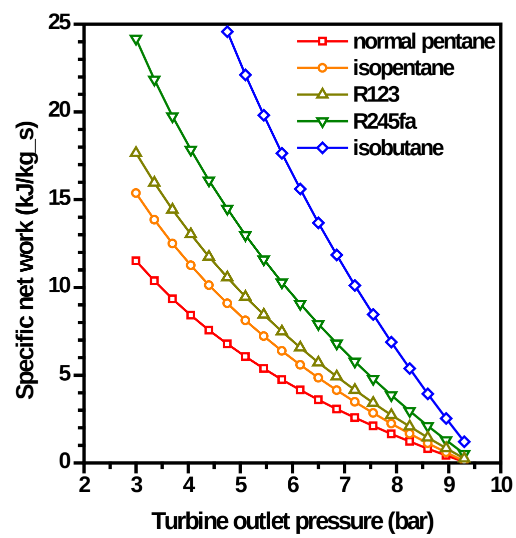

Fig. 7 Net work per unit mass of source fluid versus turbine outlet pressure for various working fluids.

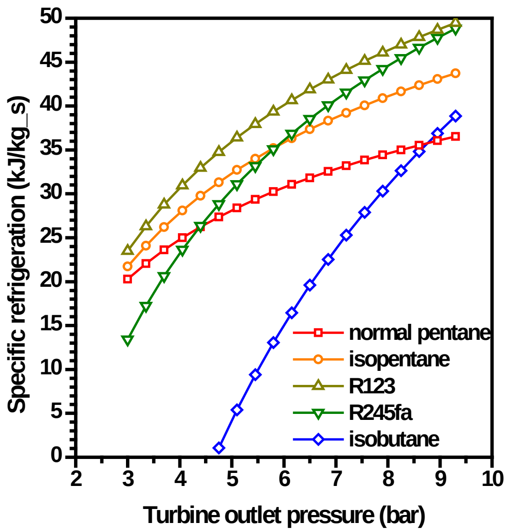

Fig. 8 Refrigeration per unit mass of source fluid versus turbine outlet pressure for various working fluids.

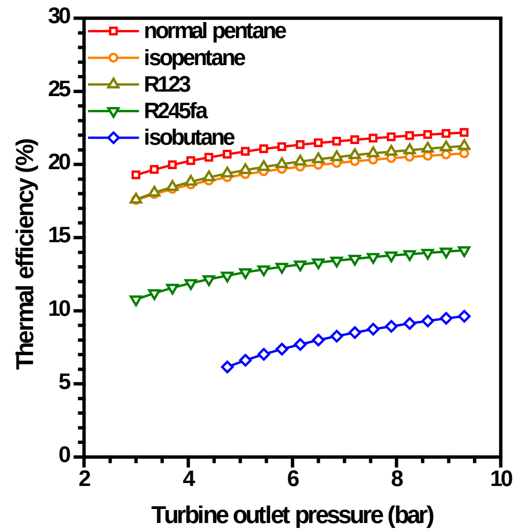

Fig. 9 Dependence of thermal efficiency on turbine outlet pressure for various working fluids.

fluid monotonically decreases with the increase of TOP and is lower for the fluid with higher critical temperature. The reason of the decreasing net work for higher TOP is because the enthalpy drop is larger if the press drop is larger.

As seen in Fig. 8, the specific refrigeration of each fluid increases with TOP. This behavior is mainly a result of an increased mass flow ratio in the evaporator, i.e. the entrainment ratio of ejector. The refrigeration capacity is proportional to the mass flow rate in the evaporator for the fixed TIT, TIP, and condenser and evaporator temperature. The relation between specific refrigeration and critical temperature of working fluid does not show a regular pattern. The specific refrigeration seems to be affected by the condenser and evaporator temperature as well as the critical temperature.

Dependence of the thermal efficiency of the combined cycle on TOP is shown in Fig. 9 for various fluids. The thermal efficiency is monotonically increasing with the increase of TOP for all fluids considered; the slope is not steep. Increasing of TOP has negative effect of specific net work and positive effect of specific refrigeration on the thermal efficiency. These two competing effects are combined to result in a flattened behavior of the thermal efficiency on TOP. Therefore there is a possibility of decreasing thermal efficiency with the increase of TOP at the higher or lower TIPs. The fluid with higher critical temperature gives higher thermal efficiency.

IV. Conclusions

For the utilization of low-temperature waste heat, the performance of a combined power and ejector refrigeration cycle is thermodynamically investigated for different working fluids. Total five kinds of dry fluids are considered for the source fluid of water with inlet temperature of 150^{o}C. Special attention is paid to the effect of turbine inlet and outlet pressure on the cycle performance such as entrainment of ejector, net work and refrigeration capacity per unit mass of source fluid, and thermal efficiency of the cycle. An exergy analysis is required to assess the effect of energy quality on the system performance. The main results of calculations are summarized as follows.

- For all fluids considered, entrainment ratio of ejector and specific refrigeration decrease almost linearly with turbine inlet pressure and increase monotonically with turbine outlet pressure.
- Specific net work has a maximum with respect to turbine inlet pressure and is smaller at lower turbine outlet pressure for all fluids considered.
- The thermal efficiency of cycle increases with turbine inlet and outlet pressure for the pressure range and working fluids considered.
- As a whole fluid with higher critical temperature gives higher entrainment ratio, lower specific net work, and higher thermal efficiency.

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