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Working Fluid Selection of Organic Rankine Cycle for a Liquid Desiccant System

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Abstract

In this study, a working fluid selection was conducted for an organic Rankine cycle (ORC). The ORC used in this study adopted the district heat source, which is rarely utilized in the cooling season. The power and heat generated from the ORC was used for a liquid desiccant system. Considering the environmental impact, n-Pentane, R1233zd(E), and Novec649 were utilized and compared with R245fa, which is one of the hydrofluorocarbons. Thermodynamic analyses of all the fluids were conducted, and Novec649 was selected owing to the high total net power and heat output. The testbed for ORC driven liquid desiccant system was developed using Novec649, and it can provide the desiccant solution at over 50°C to enter the regenerator of liquid desiccant system without requiring an auxiliary heater.

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Keywords: Organic Rankine cycle; Working fluid; Liquid desiccant; District heating

Nomenclature

h	Enthalpy (J/kg)
\dot{m}	Mass flow rate (kg/s)
η	Efficiency (-)
P	Power (kW)
\dot{Q}	Load (kW)
T	Temperature (°C)
s	Temperature (°C)
\dot{W}	Work (kW)

1. Introduction

In recent years, the applications of distributed power generation systems using small-scale combined heat and power (CHP) systems have increased in commercial buildings and apartment complexes. However, the heat generated from CHP systems, which is a relatively low-temperature heat source, is insufficiently utilized in the cooling season due to the decrease in the heat demand. Integrating the CHP system with a thermally driven cooling system can be a good alternative to increase the heat demand in the cooling season [1-3].

An organic Rankine cycle (ORC), which is one of the commercial CHP systems, uses a relatively low grade heat source to produce the heat and power upon employing organic fluid, when compared with the conventional Rankine cycle. The performance of the ORC depends mainly on the working fluid; therefore, the selection of the working fluid considering the operating temperature range is important for the ORC.

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Cho and Cho [4] recommended R245fa as the working fluid of ORC for the heat source temperature below 60°C when considering the efficiency of cycle and power generation. Darvish et al. [5] selected R134a, considering both exergy and cost at the heat source at 120°C. Gao et al. [6] selected R152a and R143a, which represent the maximum power output and minimum cost as the working fluid of ORC, respectively, using industrial waste heat.

Previous studies primarily performed the working fluid selection when using low-temperature heat sources (i.e., solar heat, industrial waste heat), but research addressing the heat produced by ORC was rare. Although employing the same heat source, various working fluids may be applied depending on the purpose of the heat from the ORC. Therefore, the selection of working fluid is required while considering the heat source, heat demand, power generation of the ORC when designing the ORC, and the environmental impact of working fluid. This study addresses the selection of low global warming potential (GWP) and ozone depletion potential (ODP) working fluid of the ORC using a district heat source for liquid desiccant (LD) system, which is one of the thermally driven cooling systems.

2. System Overview

ORCLD

The ORC used in this study consist of an evaporator, expander, condenser, and pump. Figure 1 shows the small-scale (<100 kW) ORC-driven LD (ORCLD) system as a distributed power generation system for commercial buildings and apartment complexes. The ORCLD receives the heat from the district heat source, and the heat reclaimed from the condenser is used for heating the desiccant solution in the regenerator of LD.

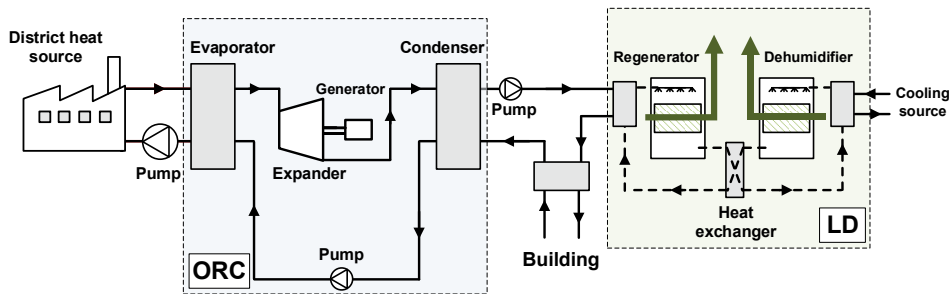


Fig. 1. Schematic of ORCLD

The district heat source was selected as a heat source for ORC operation. The hot water used for district heating, supplied at approximately 120°C, is relatively hot for direct use in apartment buildings, so hot water can be supplied upon lowering its temperature via a central heat exchanger in the apartment building. If the ORC is used instead of heat exchanger, it is possible to simultaneously supply hot water at the temperature required by the heat demand (i.e., regenerator, building) and generate electricity.

Meanwhile, the LD is a representative thermally driven cooling technology to improve the utilization of heat produced in the CHP system during summer season. The LD is mainly composed of a dehumidifier and a regenerator, with a desiccant solution circulating between them. A strong solution is required to dehumidify the process air, and it is also necessary to cool the desiccant solution for effective dehumidification. However, once the desiccant solution is used in the dehumidifier, it becomes weak; hence, a heat source is required to regenerate it.

The heat reclaimed from the condenser is preferentially utilized as the heat source for heating the desiccant solution entering the regenerator, and the remaining heat is consumed in the building. For stable ORC operation, a closed-loop system using water was applied for the heat recovery in the condenser, so the temperature of the water supplied to the condenser by the ORC was constant. The electricity produced by the ORC will be provided to run common appliances (i.e., lighting, elevator) in the building and operating pumps and fans for LD.

Working fluid selection

There are many organics that can be used as a working fluid of the ORC, and new fluids are also being developed. Because each fluid has different thermodynamic and environmental properties, the determination

of a suitable working fluid for the ORC can be an issue, and recommendations for working fluids vary among researchers. Therefore, a suitable working fluid under the given conditions should be selected. In this study, considering the environmental impact, the working fluid of ORC is recommended to heat the desiccant solution without an auxiliary heater when using the district heat source as the heat source of the ORC. The conditions for selecting a working fluid are as follows.

- Isentropic or dry fluid
- Stability
- Low flammability and toxicity
- Low cost

This work, which is built in an Engineering Equation Solver (EES) program, considered three environmentally friendly working fluids as possible alternatives to hydrofluorocarbons (HFCs). The characteristics of three working fluids are compared with those of R245fa, which is one of the representative HFCs. The characteristics of the four working fluids are listed in Table 1. All of the working fluids reviewed have zero ODP and a low GWP, except for R245fa.

Table 1. Properties of each working fluid

	R245fa	n-Pentane	Novdec649	R1233zd(E)
Boiling point [°C]	15.3	36	49	18
Molecular weight [g/mol]	134	72.15	316	130.5
Critical pressure [MPa]	3.6	3.369	1.88	3.623
Critical point [°C]	154	196.7	169	165.6
Liquid density [kg/m ³]	1,339	1,321.3	1,600	1,321.3
Heat of vaporization [kJ/kg]	190	366	95	192
Specific heat [kJ/kgK]	0.92	2.32	1.10	0.82
global warming potential [-]	1030	11	1	1
ozone depletion potential [-]	0	0	0	0

Considering the operating range of the ORCLD to select the working fluids available for the given design conditions, the previous researches showed that a desiccant solution with a temperature of at least 40°C is required to sufficiently regenerate the solution in the regenerator of LD using an aqueous lithium chloride (LiCl) solution [7,8]. In the ORC evaporator, it was assumed that a heat source at 120°C, the normal maximum temperature of district heating, is supplied. The cycle efficiency and thermodynamic characteristics of working fluids were evaluated under the design conditions of ORCLD as shown in Table 2.

Table 2. Design conditions of ORCLD

Design parameter	Value
Thermodynamic power [W]	100
ORC pump efficiency [%]	70
Expander efficiency [%]	70
Cooling source (water) inlet temperature [°C]	40
Heat source (water) inlet temperature [°C]	120
Temperature difference between heat and cooling source [°C]	15
Expander inlet temperature [°C]	115
Pressure ratio [-]	3

Thermodynamic analysis

The thermodynamic properties of all the fluids were calculated using the EES program considering the thermodynamic cycle of the ORC under the design conditions. It was assumed that power output, expander and pump efficiency, district heating and cooling water supply temperature, pressure ratio ($P_{exp,in}/P_{exp,out}$), and pinch point were all constant. Among the design conditions shown in Table 2, the flow rates of heating, cooling, and working fluids; cycle efficiency; expander pressures; pump power consumption; and duty of evaporator and condenser for working fluids were compared. The thermodynamic equations for analyzing the ORC performance are as follows (Equations 1-4).

$$\eta_{exp} = (h_{exp,in} - h_{exp,out}) / (h_{exp,in} - h_{exp,out,s}) \quad (1)$$

$$\eta_{pump} = (h_{pump,out,s} - h_{pump,in}) / (h_{pump,out} - h_{pump,in}) \quad (2)$$

$$\dot{Q}_{evap} = \dot{m}_{orc}(h_{evap,in} - h_{evap,out}) \quad (3)$$

$$\eta_{orc} = (\dot{W}_{exp} - \dot{W}_{pump}) / \dot{Q}_{evap} \quad (4)$$

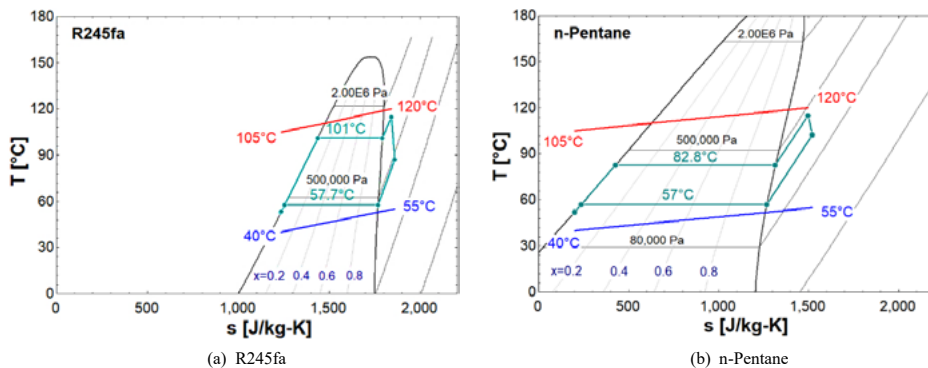
The energy inputs and outputs of the four major components of the ORC are obtained as the product of the working fluid flow rate and the inlet and outlet enthalpy differences. The enthalpy values can be obtained using the isentropic efficiency values of the expander and pump shown in Table 2 and Equations 1 and 2. Because the power generated by the expander was assumed to be 100 W, the enthalpy of each component was calculated, and the required flow rate of the working fluid could be obtained.

The heat supply in the evaporator is shown in Equation 3. Since the inlet and outlet temperature difference of heating fluid was assumed to be 15°C, the required water flow rate could be obtained. The same applied to the condenser; finally, the thermal efficiency of the cycle was calculated using Equation 4.

3. Results

The thermodynamic characteristics of the T-s diagram of the four working fluids are shown in Figure 2, and the performance characteristics of ORCLD for the working fluids are summarized in Table 3.

To produce an output of 100 W under the design conditions of Table 2, wherein 1,460 W of heat energy is shown to be required, and R245fa exhibited 6.41% of thermal efficiency. To satisfy the given design conditions, for n-Pentane, either the pressure ratio or cooling water supply temperature had to be lowered, so the pressure ratio of n-Pentane was set as 2. Although n-Pentane has the highest critical temperature and exhibits the lowest efficiency, its power output is the highest. However, n-Pentane was excluded from the final working fluid selection because it is a flammable fluid and is difficult to operate under the design conditions. The cycle efficiency was the highest in R1233zd (E), but it was determined that the actual power output was more meaningful than the cycle efficiency when utilizing wasted energy during the summer. Additionally, R245fa and R1233zd (E) operate at a relatively higher pressure to supply heat to the LD system, and it will be difficult to recover the higher temperature of water. Novec649 exhibited a relatively low efficiency due to its high molecular weight, but its actual power output was the highest, except for n-Pentane, and it was possible to obtain hotter water by increasing the pressure. It can be recommended as a suitable working fluid to be applied to the proposed system, which focuses on heat recovery.



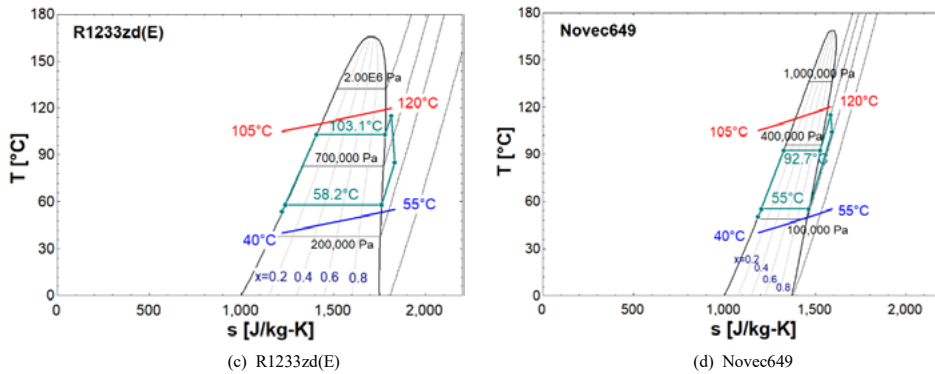


Fig. 2. T-s diagram of the working fluids

Table 3. Performance characteristics of the working fluids

	R245fa	n-Pentane	Novec649	R1233zd(E)
Efficiency [%]	6.41	4.22	4.78	6.74
Hot water flow rate [kg/s]	0.02301	0.03647	0.03192	0.02204
Cooling water flow rate [kg/s]	0.02179	0.03536	0.03076	0.02079
Working fluid flow rate [kg/s]	0.006577	0.005023	0.01407	0.0064
High pressure [kPa]	1298	394	373	1115
Low pressure [kPa]	433	197	124	372
Pressure ratio[-]	3	2	3	3
Total net power [W]	93.54	97.62	96.72	94.3
Heat input [W]	1460	2315	2026	1398
Heat generation [W]	1366	2217	1929	1304

4. Discussion

In this study, the ORCLD system was designed and developed using Novec649, which was determined to be the most suitable working fluid, and an experiment was conducted to verify the performance of the proposed system. The desired temperature of district heating was realized through the electric heater, the ORC (Figure 3) was installed at the LD part of the existing desiccant, and an evaporative cooling system called LD-IDECOAS [9] was adopted to monitor the temperature of the desiccant solution supplied to the regenerator. Therminol 55, which is a thermal fluid that attain temperatures of up to 300°C without causing toxicity to humans and the environment, was used instead of water.

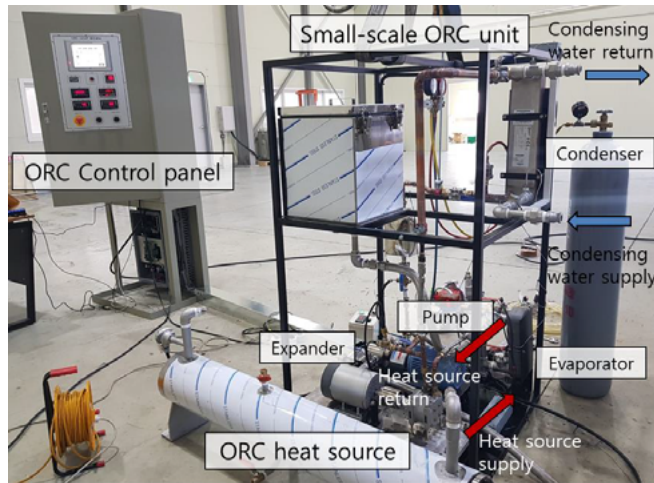


Fig. 3. Experimental setup of ORC

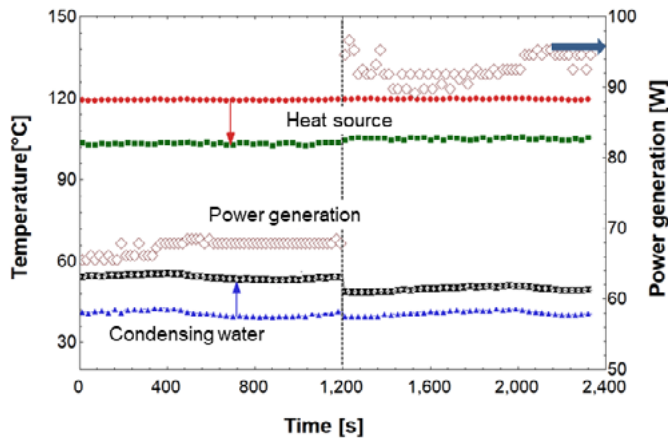


Fig. 4. Test results

The experiment result showed that the power output was 67 W, which is lower than that of the simulation condition (100 W). Moreover, the pressure ratio was 2.37 when the ORC operated with the maximum flow rate of the working fluid and heating fluid (Figure 4). In that case, the desiccant solution entering the regenerator could be supplied at a temperature of approximately 51°C. When the flow rates of the heating and working fluids were decreased while maintaining the temperature of heating fluid at 120°C, the pressure ratio was increased to 2.72, so the power output also increased to approximately 93 W. The output power in the second case was larger than that in the first case; however, in the case with higher pressure ratio, the heat transfer rate of the condenser decreased. The temperature of cooling water exiting the condenser was 50°C, which is insufficient to supply heat for regeneration in the LD regenerator.

Conclusion

In this study, the working fluid for the ORC CHP system was determined considering the environmental impact and effective utilization of the district heating, while supplying the required heat for the liquid desiccant system in the cooling season. R245fa (HFCs) and environmentally friendly working fluids such as R514A, n-

Pentane, R1233zd (E), and Nove649 were considered. When the district heat source is at 120°C, and cooling water at 40°C is supplied to the ORC, which produces 100 W of output power, Novec649 was selected as the working fluid applicable to the ORCLD. Novec649 can transfer significant heat energy to the regeneration part with the largest actual power generation, except for n-Pentane, which is a flammable fluid.

Using Novec649, a testbed for the ORCLD system was developed, and the performance of the system was investigated. The ORCLD with Novec649 could supply sufficient heat energy for the solution regeneration without requiring additional heat, and the solution inlet temperature of the regenerator was over 50°C.

Increasing the ORC power generation may also reduce the heat transfer rate that can be recovered in the condenser, so further studies must be conducted to determine an optimal operating method for the ORC to minimize the energy consumption of the LD system.

Acknowledgments

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