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Proceedings of the 7th International Seminar on ORC Power Systems

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A NOVEL APPROACH TO DISTRICT HEATING: USING A TWO-PHASE EXPANDER IN REVERSIBLE HEAT PUMP-ORGANIC RANKINE CYCLE SYSTEM

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ABSTRACT

A district heating system involves a central generation and distribution of heat to residential buildings through a network of insulated pipes. Heat can be generated, for example, from the combustion of fossil fuels and biomass. Since there are many environmental restrictions and the growth of heat and energy demand, several industrial waste heat and renewable energy sources, such as geothermal or solar thermal energy may be promising to be utilized for district heating purposes. However, in some districts, various low-temperature heat sources might be available; as a result, a heat pump is installed to increase the temperature to accommodate demand peak loads. The heat pump is operated only for a certain period and sometimes not used during summer. To optimize the utilization of the heat source, the district heating system may be transformed into a power generation system that can generate, for example, electricity instead of heat during the summer. This goal may be achieved by applying a reversible system. Therefore, this article discusses the novel reversible heat pump-organic Rankine cycle (RHPORC) system using a two-phase expansion system. Some working fluids were selected based on thermal properties, as well as safety and environmental issues. Some selected two-phase volumetric expanders were introduced in the novel system. In the end, the performances of the system based on the selected working fluid were compared. According to the results of a study, using RHPORC in district heating systems might save annual energy consumption by up to 50%.

1 INTRODUCTION

For more than a century, commercial district heating systems have been running at high temperatures to meet demand, and they are often fueled by fossil fuels. The fourth generation of district heating systems, in which low-temperature district heating (LTDH) uses renewable energy, may play a key role in the EU's effort to reduce the dependency on fossil fuels to heat buildings (Averfalk *et al*., 2021). In this case, low-temperature does not relate to a particular temperature range in absolute terms; instead, it refers to the set of temperatures in the district energy network or the available energy source (e.g., solar thermal, waste heat, geothermal, and so on) under consideration (Bertelsen *et al*., 2021).

Some recent articles (Buffa *et al*., 2019; Sarbu *et al*., 2022) reviewed and reported the integration of renewable energy sources for district heating systems focused on the low-temperature system where the utilization of the fifth generation of district heating and cooling (DHC) system has been introduced. Multi-low-temperature renewable energy sources operated in bivalent parallel or serial modes could also be introduced to meet the heating demands (Buday and Buday-Bódi, 2023). Nevertheless, relying on low-temperature renewable heat sources was insufficient to fulfil demand during the peak hour (Kontu *et al*., 2019; Østergaard and Andersen, 2018). As a result, a heat pump may be the most effective means of increasing the temperature and satisfying demand. Furthermore, in the literature, a few articles (Marty *et al*., 2018; Mikielewicz *et al*., 2022; Wang *et al*., 2018) reported the performance of the LTDH system simultaneously operated with organic Rankine cycle (ORC). In that case, the ORC operates using an available surplus heat (e.g., when a load of district heating demand is low during summer). Moreover, this ORC is installed in a stand-alone system, making the investment cost more expensive and not attractive for investors. As a result, an alternative or improved design is required to enhance the LTDH system that will be introduced and described in this article.

This article aims to present a viable solution for an LTDH system using a heat pump and ORC. There is growing interest in using low-temperature heat sources from renewable sources, including solar thermal, geothermal, waste heat, biomass, and so on. The novel reversible heat pump-organic Rankine cycle (RHPORC) system employing two-phase expander is introduced as an alternative design for LTDH regarding the operation and load of heating demand. Some volumetric expanders such as screw, multi-vane, or scroll might be used to do so, even though two-phase expansion might be avoided due to a common problem (e.g., blade erosion) in turbomachinery (Daniarta and Kolasiński, 2021; Francesconi *et al*., 2022; van Heule *et al*., 2022). Moreover, this article compared the system using only a heat pump or RHPORC. A case study of LTDH was given including the assumed period time and two different working fluids to demonstrate the performance of RHPORC. In the end, the benefit of using RHPORC is described.

2 REVERSIBLE HEAT PUMP-ORGANIC RANKINE CYCLE SYSTEM AND A CASE STUDY

DHC could enable the integration of low-grade renewable heat sources like geothermal, waste heat, solar thermal energy, and so on, even while the majority of DHC systems are still powered by coal and natural gas. The International Renewable Energy Agency (IRENA) reported that the percentage of renewable energy in district heating might rise from 8% in 2017 to 77% in 2050 (IRENA, 2020). It is found that the different local heat sources available in a given area make it challenging to maintain the same operating temperatures for district heating networks. Therefore, a proper selection of low-temperature heat sources, which is suitable to meet the base demand, is required. Although many various heat sources might be available in a district, we describe only one case in this paper. For this example, the geothermal energy source is chosen to meet a load of heating demand illustrated in Figure 1, and then the heat and the temperature level are raised using the heat pump to satisfy the peak demand. 170

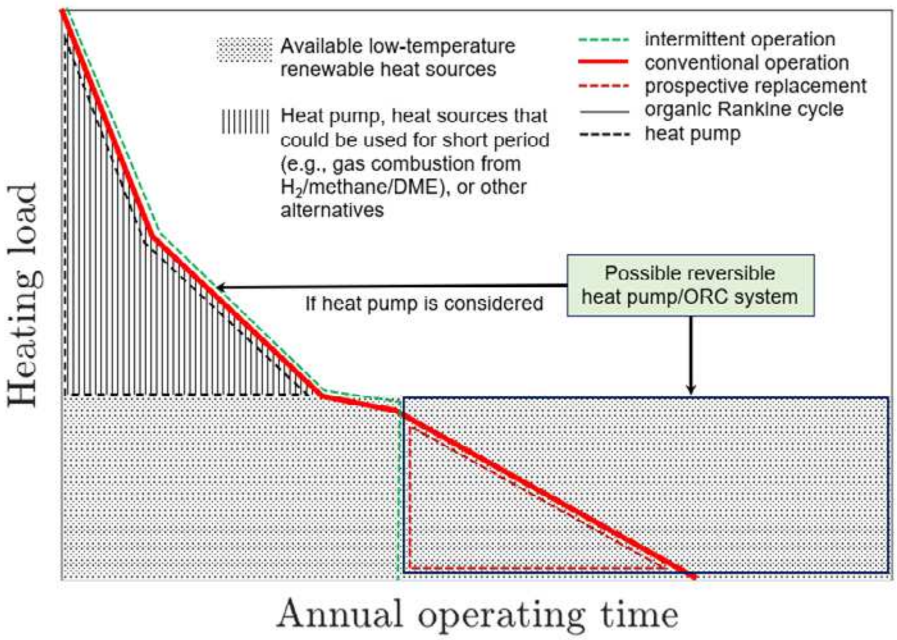
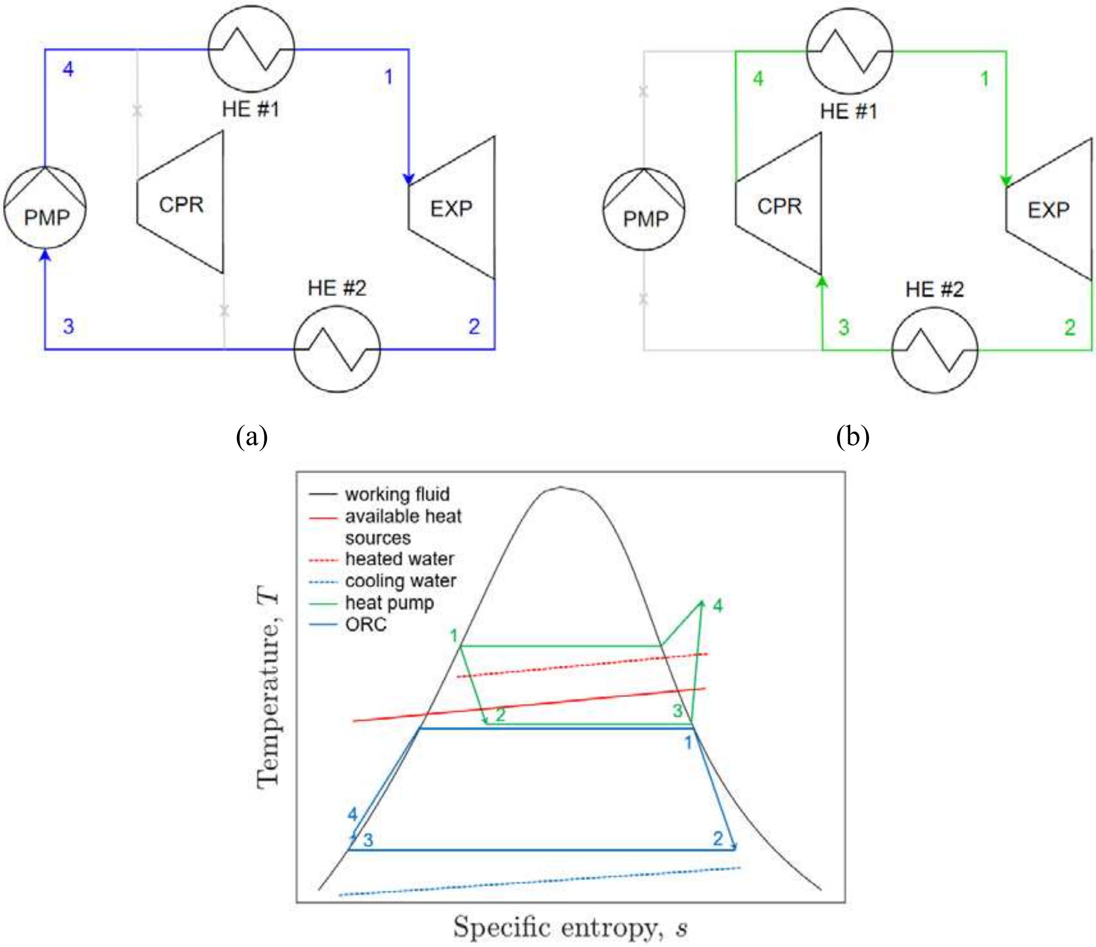


Figure 1: An illustration of an operating system for a case

To supply the base demand, the LTDH system uses geothermal at least 5,000 hours (Nuytten *et al.*, 2013), assuming the system runs intermittently rather than continuously as illustrated in Figure 1. Moreover, to meet the peak demand, the heat pump must run for 3,000 hours (Kallert *et al.*, 2017), and the gas combustion (H_2, methane or biogas) has to run for 2,000 hours. Given that there is no need for heating during 3,760 of the 8,760 hours in a year, geothermal energy is not utilized. Therefore, geothermal energy might also be used to produce electricity via ORC. Installing ORC with new components might require a higher financial investment. We propose designing the RHPORC system since the heat pump also plays a key role in this LTDH system and is utilized, but only occasionally, to increase its competitiveness. For further analysis, we assumed this RHPORC system operates 3,000 hours as a heat pump and 3,760 hours as ORC as illustrated in Figure 2.



(a) (b)

(c)

Figure 2: A novel reversible heat pump-organic Rankine cycle (RHPORC) (a) in ORC mode, (b) in heat pump mode, and (c) its thermodynamic process in *T-s* diagram, where HE, EXP, PMP, CPR describe as the heat exchanger, expander, pump, and compressor, respectively.

The RHPORC is designed using two heat exchangers (as condenser and evaporator), a pump (for ORC), a compressor (for heat pump), and an expander (for both heat pump and ORC). In a different application, the RHPORC system has been introduced (Daniarta *et al.*, 2022; Francesconi *et al.*, 2022; Wieland *et al.*, 2023). The list of the components shown in Figure 2 is described in Table 1 along with the specific process that is expressed as a function of mass and energy balance using Equations (1) and (2), where $\dot{m}$, h, $\dot{W}$, and $\dot{Q}$ represent the mass flow rate, specific enthalpy, power, and heat transfer rate, respectively.

$$\sum \dot{m}_{\text{in}} = \sum \dot{m}_{\text{out}} \quad (1)$$

$$\dot{Q} + \sum \dot{m}_{\text{in}} h_{\text{in}} = P + \sum \dot{m}_{\text{out}} h_{\text{out}} \tag{2}$$

The described model in this study was implemented in MATLAB and simulation was performed using thermal properties data taken from REFPROP 10.0 (Lemmon *et al.*, 2018). In this case, some assumptions are taken into account as follows. Dimethyl ether (DME or RE170) and 1,1-Difluoroethane (R152a) are selected as working fluids as they have a relatively low negative environmental effect (i.e., in global warming potential and ozone depletion potential). Assuming the geothermal heat is taken at 80°C (at 300 kPa) and the water is heated up to 100°C using a heat pump, where the pinch point temperature is 5°C. Each component operates in a steady-state condition. Heat exchangers operate with constant pressure, constant overall heat transfer coefficient, and constant specific heat. The change of kinetic and potential energy of the stream in the heat exchangers is negligible. Moreover, there are no heat or pressure losses. For some rotating components, such as the compressor, pump, and expander, the isentropic efficiency is assumed at 0.8. The isentropic efficiency of the expander for heat pump mode is assumed to be 0.5. Therefore, the coefficient performance (COP) of the heat pump and the efficiency of ORC could be determined in this RHPORC.

Table 1: List of RHPORC components and specific processes referred to in Figure 2

List of component	Specific enthalpy (ORC mode) (kJ/kg)	Specific enthalpy (heat pump mode) (kJ/kg)	Mass flow rate (kg/s)	Product (kW)
HE #1	$h_{\text{ORC.1}} - h_{\text{ORC.4}}$	$h_{\text{HP.4}} - h_{\text{HP.1}}$	$\dot{m}_{\text{wf}}$	$\dot{Q}_{\text{ORC,HE1}}$, $\dot{Q}_{\text{HP,HE1}}$
Expander	$h_{\text{ORC.1}} - h_{\text{ORC.2}}$	$h_{\text{HP.1}} - h_{\text{HP.2}}$	$\dot{m}_{\text{wf}}$	$P_{\text{ORC,EXP}}$, $P_{\text{HP,EXP}}$
HE #2	$h_{\text{ORC.2}} - h_{\text{ORC.3}}$	$h_{\text{HP.3}} - h_{\text{HP.2}}$	$\dot{m}_{\text{wf}}$	$\dot{Q}_{\text{ORC,HE2}}$, $\dot{Q}_{\text{HP,HE2}}$
Pump	$h_{\text{ORC.4}} - h_{\text{ORC.3}}$	-	$\dot{m}_{\text{wf}}$	$P_{\text{ORC,PMP}}$
Compressor	-	$h_{\text{HP.4}} - h_{\text{HP.3}}$	$\dot{m}_{\text{wf}}$	$P_{\text{HP,CPR}}$

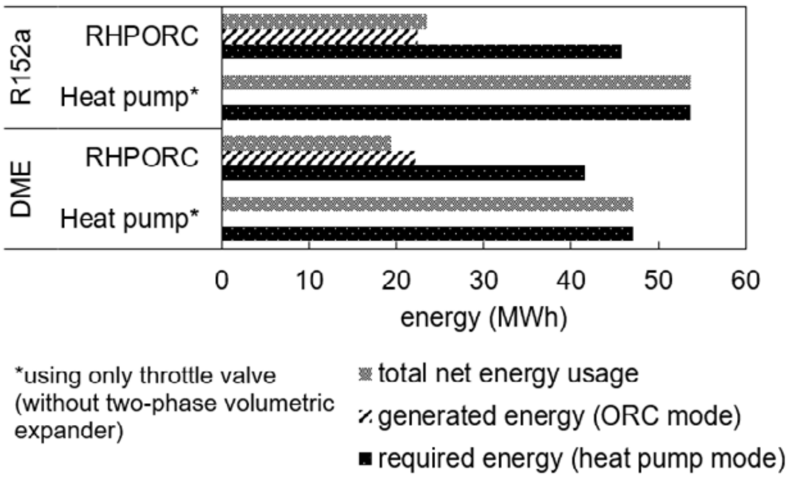
3 RESULT AND DISCUSSION

The used MATLAB configuration was taken from (Daniarta *et al.*, 2022), where the model has been validated. Moreover, the obtained simulation result is described in Figure 3 which compares the required and generated energy, and rejected heat between four different scenarios, each with a specific working fluid (DME and R152a) and specific design (RHPORC and only heat pump with throttle valve). In this study, the model did not involve a quasi-dynamic simulation of the system, only a method that assumes the system operates at the condition above mentioned. Moreover, the heating load supplied by the heat pump was assumed to be constant. The obtained mass flow rates of the heat pump and the ORC based on this simulation are 0.30 kg/s and 0.18 kg/s, respectively.

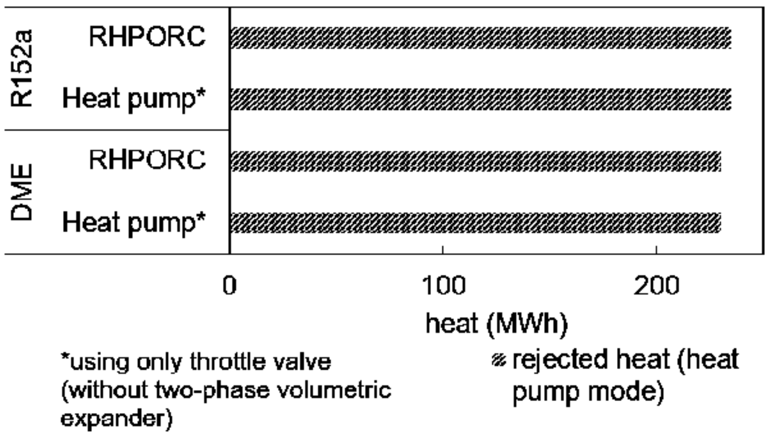
The result indicates that utilizing various working fluids may lead to varying amounts of heat being rejected; for example, the heat pump using R152a as working fluid might reject heat up to 234.45 MWh, which is 4.32 MWh more than in the case of the same configuration using DME. A heat pump using only a throttle valve (i.e., without a two-phase volumetric expander) tends to require more energy. This heat pump requires 53.66 MWh of electricity for R152a (with COP of 3.51) and 47.12 MWh for DME (with COP of 4). This energy consumption could be reduced up to 7.82 MWh (for R152a) and 5.59 MWh (for DME) by introducing the two-phase volumetric expansion (integrated with the generator) to replace the throttle valve. Moreover, the COP of the heat pump mode (RHPORC) could be 4.11 and 4.54 for R152a and DME, respectively.

The introduction of the RHPORC appears to hold promise since, as mentioned in the previous section, the heat pump might be switched into ORC operating mode to generate electricity when there is an excess of heat (during the summer). The ORC makes use of shared components like heat exchangers and expanders. As shown in Figure 2, the expander utilized in the heat pump mode is likewise used in ORC mode. The result from the mathematical modelling (presented in Figure 3) indicates that ORC employing R152a and DME may produce energy of 22.45 MWh and 22.20 MWh, respectively. Using the above-mentioned assumption, the efficiency of RHPORC in ORC mode for R152a and DME could be up to 7.39% and 7.47%, respectively. This study shows that the district heating system employing RHPORC uses less energy overall, with the total net energy usage of the system being 23.39 MWh (R152a) and 19.32 MWh (DME).

The results show that RHPORC offers a perspective in the district heating system with reasonably low annual energy consumption based on the aforementioned mathematical modelling result. Nonetheless, it is important to pay close attention to the design of the two-phase expander. As an alternative to a turbine, a volumetric rotating expander (such as a screw, multi-vane, or scroll) might be used in this RHPORC as these expanders could operate in two-phase conditions (Daniarta and Kolasiński, 2021; Francesconi *et al*., 2022; van Heule *et al*., 2022). Moreover, the design of a two-phase volumetric expander might be conducted based on the feature of volumetric machines operating in both heat pump and ORC mode that pressure and volumetric expansion ratio are the parameters that must be considered.



(a)



(b)

Figure 3: The obtained result in (a) required and produced energy (both heat pump and ORC mode), and (b) the rejected heat (heat pump mode)

4 CONCLUSIONS

This paper introduced the RHPORC (a reversible thermodynamic system which could be operated as a heat pump and ORC) that might be used to improve the district heating system. The study also discusses the comparison between the RHPORC system and a conventional heat pump with a throttle valve. The comparison between two different working fluid (i.e., R152a and DME) were examined. The result shows that RHPORC using DME offers better efficiency in ORC mode than in the case of the application of R152a. However, using R152a in heat pump mode might offer more rejected heat than DME. Moreover, the results of the study show that introducing RHPORC in district heating systems could reduce up to 50% of annual energy consumption, but the design of a two-phase volumetric expander needs to be considered carefully.

NOMENCLATURE

COP	the coefficient performance	(-)
h	specific enthalpy	(kJ/kg)
$\dot{m}$	mass flow rate	(kg/s)
P	power	(kW)
$\dot{Q}$	heat transfer rate	(kW)

Subscript

CPR	compressor
EXP	expander
HE1	heat exchanger 1
HE2	heat exchanger 2
HP	heat pump
PMP	pump
wf	working fluid

Abbreviations

DHC	district heating and cooling
DME	dimethyl ether
LTDH	low-temperature district heating
ORC	organic Rankine cycle
RHPORC	reversible heat pump-organic Rankine cycle

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This book contains the compilation of works contributed to the *7th International Seminar on Organic Rankine Cycle Power Systems* (ORC 2023), held in Seville between the 4th and 6th of September 2023. The event was hosted by Universidad de Sevilla on behalf of the Knowledge Centre on Organic Rankine Cycle Technology (KCORC), incorporated in The Netherlands.

The ORC conference, organized biennially, stems as the only conference that is specific to ORC technology, therefore gathering a diverse community whose affiliation spans across all the interested stakeholders, not only in this particular technology but also and in a broader context, in the energy transition. Original equipment manufacturers, professional associations, end-users, investors, policy makers, academics, scientists feel at home at ORC 2023.

The almost 100 proceedings in this book cover a wide variety of topics, from fundamentals to system integration through component design, accounting for thermodynamic performance as well as component design. In addition to this, and as a new track in 2023, works on heat pump technology were also accepted in order to raise awareness of the strong ties between both technologies, specifically in energy storage applications.

This book provides an excellent overview of the current maturity of power systems based on Organic Rankine Cycle technology for applications as diverse as geothermal and waste heat recovery in industry or downstream of other prime movers (e.g., marine applications). It is also an excellent source of information to understand the current challenges faced by the technology, stemming from a very competitive market and increasingly stringent environmental regulations.

The organizers of ORC 2023 hope that the reader finds this work as exciting as the attendees to the conference and, maybe, make the decision to join the 8th edition to the conference in 2025.

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