

David Tomás Sánchez Martínez
Lourdes García Rodríguez
(coordinadores)

Proceedings of the 7th International Seminar on

ORC

Power Systems

Editorial Universidad de Sevilla

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Diseño de cubierta y maquetación: los autores

INDEX OF CONTRIBUTIONS

ID3 - Additive manufacturing for fast prototyping of a velocity compounded radial re-entry turbine Authors: Dominik Stümpfl, Karel Ráž, Philipp Streit, Andreas P. Weiß	13
ID4 - Thermodynamic concept of a novel recuperative two-phase power cycle process Authors: Benedikt G. Bederna, Riley B. Barta, Christiane S. Thomas.	23
ID7 - Performance analysis of a 1.5 MW Organic Rankine Cycle in a Carnot battery system for grid balancing services Authors: Robin Tassenoy, Hannes Van De Velde, Kenny Couvreur, Michel De Paepe, Steven Lecompte	33
ID8 - Calibration of multi-hole probes for measurements in compressible organic vapor flows Authors: Leander Hake, Stephan Sundermeier, Stefan Aus Der Wiesche, Maximilian Passmann	43
ID9 - pocketORC: A browser-based calculator for teaching organic Rankine cycle power systems Authors: Martin White	53
ID10 - Evaluation of existing supercritical heat transfer correlations for designing the vapor generator in low-temperature transcritical Organic Rankine Cycle systems Authors: Jera Van Nieuwenhuyse, Anastasios Skiadopoulos, Dimitris Manolakos, Steven Lecompte, Michel De Paepe	61
ID12 - A novel combined cooling and power cycle integrated ejector refrigeration and composition adjustment for stationary engine waste heat recovery Authors: Xiaocun Sun, Lingfeng Shi, Hua Tian, Gequn Shu	71
ID14 - Design and construction of a reversible ORC test rig for geothermal CHP applications Authors: Florian Kaufmann, Christopher Schiffler, Christoph Wieland, Hartmut Spliethoff	81
ID15 - Robust and fast meanline methodology for radial inflow turbines with non-ideal gases for system level optimisation of organic Rankine cycles Authors: Carola Freytag, Eva Alvarez-Regueiro, Pablo Ale-Martos, Esperanza Barrera-Medrano, Ricardo Martinez-Botas.	91
ID16 - Shape optimization of a sCO ₂ centrifugal compressor stage Authors: Alessandro Romei, Paolo Gaetani, Giacomo Persico	101
ID17 - Optimizing the performance of a hybrid solar-biomass micro-CHP system with a TFC engine as the prime mover for domestic applications Authors: Anastasios Skiadopoulos, Xander Van Heule, Steven Lecompte, Michel De Paepe, Dimitrios Manolakos	109
ID19 - Systematic and multi-criteria optimisation of subcritical thermally integrated Carnot batteries (TI-PTES) in an extended domain Authors: Antoine Laterre, Olivier Dumont, Vincent Lemort, Francesco Contino	119

ID20 - ORC technology used in a heat removal system for an advanced nuclear power plant Authors: Guillaume Lhermet, Benoit Payebien, Nicolas Tauveron, Nadia Caney, Franck Morin	130
ID22 - Assessment of trilateral Organic Rankine Cycle for solar applications with innovative turboexpander concept Authors: Alessandro Romei, Andrea Giostri, Andrea Spinelli.	140
ID25 - Evaluation of the performance of an axial one-stage 10kW turbogenerator through experimental testing Authors: Piotr Klimaszewski, Piotr Klonowicz, Lukasz Witanowski, Tomasz Suchocki, Piotr Lampart, Eugeniusz Ihnatowicz, Lukasz Antczak, Dawid Zaniewski, Lukasz Jedrzejewski	149
ID26 - Investigation of the turbulence level and the vortex shedding in a turbine cascade working with an organic vapor at subsonic Mach numbers Authors: Leander Hake, Stephan Sundermeier, Stefan Aus Der Wiesche, Camille Matar, Paola Cinnella, Xavier Gloerfelt	159
ID27 - A novel approach to district heating: using a two-phase expander in a reversible heat pump-Organic Rankine Cycle system Authors: Sindu Daniarta, Attila R. Imre, Piotr Kolasinski	169
ID28 - Optimization of a partially evaporating Organic Rankine Cycle with thermal non-equilibrium expansion Authors: Xander Van Heule, Tasos Skiadopoulos, Dimitris Manolakos, Michel De Paepe, Steven Lecompte	176
ID29 - Cost-effective option of cold energy utilization in pharmaceutical industry Authors: Sindu Daniarta, Dawid Sowa, Ádám Havas, Attila R. Imre, Piotr Kolasinski	184
ID30 - Numerical investigation of a transonic dense gas flow over an idealized blade vane configuration Authors: Aurelien Bienner, Xavier Gloerfelt, Paola Cinnella, Leander Hake, Stefan Aus Der Wiesche	193
ID31 - Comprehensive analysis of ORC-VCC system for air conditioning from low-temperature waste heat Authors: Lukasz Witanowski	203
ID33 - Pareto front analysis for the design and the working fluid selection in ORC-based pumped thermal energy storage technology in both pure electric and cogenerative applications Authors: Marco Astolfi, Dario Alfani, Andrea Giostri	214
ID36 - Evaluating the waste heat sources in a very large crude carrier and the potential integration of Organic Rankine Cycle configurations Authors: Amalia Stainchaouer, Christopher Schiffler, Christoph Wieland, Hartmut Spliethoff	224
ID37 - Investigating R1234ze and R1234yf as replacements to R134a in waste heat recovery ORC applications Authors: James Bull, James Buick, Jovana Radulovic	234

ID38 - Performance and economic assessment of a thermally integrated reversible HP/ORC Carnot battery applied to data centers Authors: Chiara Poletto, Andrea De Pascale, Saverio Ottaviano, Olivier Dumont, Maria Alessandra Ancona, Michele Bianchi	244
ID39 - Evaluation of the performance of multiple supercritical CO ₂ power cycles in Waste Heat Recovery applications Authors: Hicham Chibli, Matthew Read, Abdalnaser Sayma	254
ID40 - Design and modeling of a demonstration-scale ORC cycle for the Liquid Air Combined Cycle Authors: Owen Pryor, William Conlon, Aaron Rimpel, Milton Venetos.....	264
ID41 - Guidelines and optimization criteria of a machine learning-based methodology for mixture design in ORC systems Authors: Valerio Mariani, Saverio Ottaviano, Andrea De Pascale, Giulio Cazzoli, Lisa Branchini, Gian Marco Bianchi	273
ID45 - Potential of trigenerative Waste Heat Recovery CO ₂ -mixture transcritical power plants for increasing the sustainability of district heating and cooling networks Authors: Mattia Baiguini, Michele Doninelli, Ettore Morosini, Dario Alfani, Gioele Di Marcoberardino, Paolo Giulio Iora, Giampaolo Manzolini, Costante Mario Invernizzi, Marco Astolfi	282
ID46 - Thermodynamic analysis of a novel pumped thermal energy storage system with waste heat integration Authors: Meiyang Zhang, Lingfeng Shi, Peng Hu, Gang Pei, Gequn Shu	294
ID48 - Pressure profile optimisation of a nozzle for wet-to-dry expansion Authors: Pawel Ogrodniczak, Abdalnaser Sayma, Martin T. White.....	304
ID51 - Thermodynamic modification of CO ₂ -based combined cooling and power cycle with ejector Authors: Yonghao Zhang, Lingfeng Shi, Gequn Shu	313
ID53 - Selection of suitable working fluid and storage material for ORC coupled with Thermal Energy Storage Authors: Dawid Sowa, Sindu Daniarta, Piotr Kolasinski	323
ID54 - Influence of dopant fluorination on the heat transfer behaviour of CO ₂ -based mixtures in transcritical power cycles Authors: Michele Doninelli, Gioele Di Marcoberardino, Costante Mario Invernizzi, Paolo Giulio Iora	333
ID57 - On air-cooled condensers for ORC systems operating with zeotropic mixtures Authors: Lorenzo Galieti, Carlo De Servi, Dario Alfani, Paolo Silva, Paola Bombarda, Piero Colonna	344
ID58 - Experiments on supersonic ORC nozzles in linear cascade configuration Authors: Marco Olivetti, Marco Manfredi, Giacomo Persico, Andrea Spinelli, Paolo Gaetani, Vincenzo Dossena	354
ID59 - Numerical analysis of aerodynamics and performance of a radial-inflow micro-ORC turbine Authors: Fatemeh Ardaneh, Marta Zocca, Antti Uusitalo, Teemu Turunen-Saaresti.	363

ID61 - ORC system using R1233zd(E) for waste heat recovery from the upstream process Authors: Meng Soon Chiong, Bemgba Nyakuma, Nur Izwanne Mahyon, Srithar Rajoo, Eva Alvarez-Regueiro, Maria Esperanza Barrera-Medrano, Ricardo F. Martinez-Botas, Yossapong Laoonual	373
ID63 - Experimental investigation of a small-scale reversible high temperature heat pump – Organic Rankine Cycle system for industrial Waste Heat Recovery Authors: Rahul Velanparambil Ravindran, Donal Cotter, Christopher Wilson, Ming Jun Huang, Neil Hewitt.	381
ID64 - Technical comparison and evaluation of a Pumped Thermal Energy Storage with two different designs Authors: Márcio Santos, Jorge André, Ricardo Mendes, José Ribeiro.	391
ID68 - The potential of CO ₂ -Plume Geothermal (CPG) Systems for CO ₂ component manufacturers: opportunities and development needs Authors: Christopher Schiffelechner, Jasper De Reus, Hartmut Spliethoff, Martin O. Saar, Sebastian Schuster, Dieter Brillert	400
ID69 - Development of a generalised low-order model for twin-screw compressors Authors: Florian Kaufmann, Ludwig Irrgang, Christopher Schiffelechner, Hartmut Spliethoff.	410
ID71 - Decision-making matrix for the selection of mixture in ORC applications Authors: William Combaluzier, Nicolas Tauveron, Michel Beaughon, Aldo Serafino.	420
ID72 - Reversible heat pump-ORC pilot plant – Experimental results and fluid charge optimization Authors: Maximilian Weitzer, Sebastian Kolb, Dominik Müller, Jürgen Karl	430
ID73 - Performance of Organic Rankine Cycle system in combination with residual municipal solid waste gasification: a simulation analysis Authors: Luca Cioccolanti, Giovanni Biancini, Ramin Moradi, Luca Del Zotto, Matteo Moglie	439
ID74 - Enhancing knowledge of engineering students at all levels on organic rankine cycle systems for their application in the built environment Authors: Luca Cioccolanti, Ramin Moradi, Ermira Abdullah, Syamimi Saadon, Mohamad Yusof Idroas, Teoh Yew Heng, Kwanchai Kraitong	449
ID75 - Studying carbon dioxide and acetone mixtures in a single-stage absorption-compression cycle for heating and cooling applications Authors: Jesús Gómez-Hernández, Ali Kholghi, Mercedes De Vega, Javier Villa, Ronan Grimes	458
ID77 - Valorising thermal composite recycling processes using Organic Rankine Cycles for combined heat and power applications Authors: Ramin Moradi, Liu Yang	466
ID80 – Prediction of the ideal maximum operational temperature of hydrocarbon and HFCs as working fluids of Organic Rankine Cycle power plants based on transition state theory Authors: Wei Yu, Chao Liu, Xijie Ban, Zhirong Li, Tianlong Yan	476
ID82 - Comparison of different evaporator topologies for industrial heat pumps Authors: Sanjay Vermani, Nitish Anand, Johan Van Bael, Evgueni Toulankine, Aldo Serafino, Carlo De Servi.	486

ID83 - On the plant improvement of Solar-driven ORC based power unit for domestic microcogeneration Authors: Fabio Fatigati, Marco Di Bartolomeo, Arianna Coletta, Diego Vittorini, Giammarco Di Giovine, Davide Di Battista, Roberto Cipollone.	496
ID84 - Mapping the techno-economic potential of next-generation CSP plants running on transcritical CO ₂ -based power cycles Authors: Pablo Rodríguez-deArriba, Francesco Crespi, Sara Pace, David Sánchez	505
ID86 - Achieving 45% micro gas turbine efficiency through hybridization with Organic Rankine Cycles Authors: Antonio Escamilla, David Sánchez Martínez, Lourdes García-Rodríguez	515
ID88 - Operational optimisation of the main heat rejection unit of CSP plants based on carbon dioxide mixtures Authors: Francesco Crespi, Pablo Rodríguez-deArriba, Lourdes García-Rodríguez, David Sánchez.	525
ID89 - Mechanical design and rotor-dynamic analysis of the ORCHID turbine Authors: Matteo Majer, Steven Chatterton, Ludovico Dassi, Alessio Secchiaroli, Edoardo Gheller, Carlo De Servi, Paolo Pennacchi, Piero Colonna, Matteo Pini.	535
ID91 - Thermodynamic feasibility of a pumped thermal energy storage driven by ocean temperature gradient Authors: Alessandra Ghilardi, Andrea Baccioli, Guido Francesco Frate, Lorenzo Ferrari	545
ID92 - Exergy-based methods for heat pumps Authors: Mathias Hofmann, Jonas Freißmann, Malte Fritz, Jeremias H. Alexe, Francesco Witte, George Tsatsaronis	553
ID93 - Reduced order modelling of optimized heat exchangers for maximum mass-specific performance of Airborne ORC Waste Heat Recovery units Authors: Fabio Beltrame, Dabo Krempus , Piero Colonna, Carlo De Servi.	563
ID97 - Basic design of an ORC demonstrator system for implementation in an Iron & Steel plant through the DECAGONE project Authors: Magnus Windfeldt, Han Deng, Trond Andresen, Christopher Schiffler	574
ID98 - Analytical estimation of the presence of non-condensable gases in the condensate tank of an Organic Rankine Cycle Authors: Radheesh Dhanasegaran, Antti Uusitalo, Juha Honkatukia, Teemu turunen-Saaresti	584
ID101 - Advanced control of compressor inlet temperature in supercritical CO ₂ Brayton cycle Authors: Rui Wang, Xuan Wang, Hua Tian, Gequn Shu.	596
ID103 - Potential for surplus-heat-to-power conversion in current and future aluminium production processes with off-gas recycling Authors: Jonas Bueie, Magnus Windfeldt, Trond Andresen.	605
ID104 - Investigating the application range of ORC power plants for the exploitation of two-phase geothermal resources Authors: Tristan Merbecks, Claudio Pietra, Paola Bombarda, Martin O. Saar, Paolo Silva, Dario Alfani.	615
ID109 - Cold Energy Recovery in LNG plants with Organic Rankine Cycle Authors: Gabriele Marchiori, Marta Giudici, Giorgia Ruffato, Marco Astolfi	626

ID110 - Numerical investigation of organic vapor flow effects on a micro-scale radial turbocompressor Authors: Andrés Sebastián, Rubén Abbas, Manuel Valdés	636
ID112 - Design, modeling and simulation of an experimental Rankine PTES system Authors: Mario Petrollese, Giorgio Cau, Matteo Marchionni, Marcello Lorenzo Marroccu, Rosa Merchan	645
ID113 - Small-scale turbopumps for Waste Heat Recovery applications based on an Organic Rankine Cycles, modeling, analytical and experimental investigation Authors: Sajjad Zakeralhoseini, Jürg Schiffmann	655
ID116 - Double-stage ORC system based on various temperature waste heat sources of the negative CO2 power plant Authors: Kamil Stasiak, Pawel Ziolkowski, Dariusz Mikielewicz	665
ID117 - Optimization of organic Rankine cycle in ocean thermal energy conversion based on NSGA-II Authors: Zheng Hu, Jiufa Chen, Bing Guo, Chengbin Zhang	679
ID118 - TES4Trig: Development of a demonstrator for the production of electricity, heating and cooling based on an Organic Rankine and an Ejector Cooling Cycle driven by high-temperature parabolic trough collectors with thermal energy storage Authors: Konstantinos Braimakis, Dimitrios Tziritas, George Stavrakakis, Julio Terrón Gutiérrez, Siddhart Dutta, Christos Xynos, Panagiotis Zervas, Sotirios Karellas	689
ID119 - Simulation and operation of a CSP that works with a HRB Cycle Authors: Antonio J. Subires, Antonio Rovira	701
ID123 - Towards a green energy community: integration of micro-ORCs combined with renewable energy technologies in buildings Authors: Diego Antonio Rodríguez Pastor, Víctor Manuel Soltero Sánchez, Elisa Carvajal Trujillo, José Antonio Becerra, Ricardo Chacartegui	713
ID129 - Assessment of high temperature heat pump layouts equipped with a bladeless turboexpander Authors: Matteo Passalacqua, Simone Maccarini, Stefano Barberis, Alberto Traverso	723
ID133 - Selection of the optimal working fluid in an Organic Rankine Cycle for Waste Heat Recovery through multi-objective optimization and decision making Authors: Bipul Krishna Saha, El Mouatez Billah Messini, Syed J. Hoque, B Aneesh Bhat, Pramod Kumar	733
ID139 - Dual condensing pressure ORC for cryogenic energy storage Authors: William M. Conlon, Milton J. Venetos	743
ID141 - Optimum coupling of thermal energy storage and power cycles for Carnot batteries Authors: Salvatore Guccione, Rafael Guede	751
ID142 - Aerodynamic design and numerical analysis of a counter-rotating centrifugal compressor Authors: Cheikh Brahim Abed, Arthur Leroux	761

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%.

169

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; Mikielwicz *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.

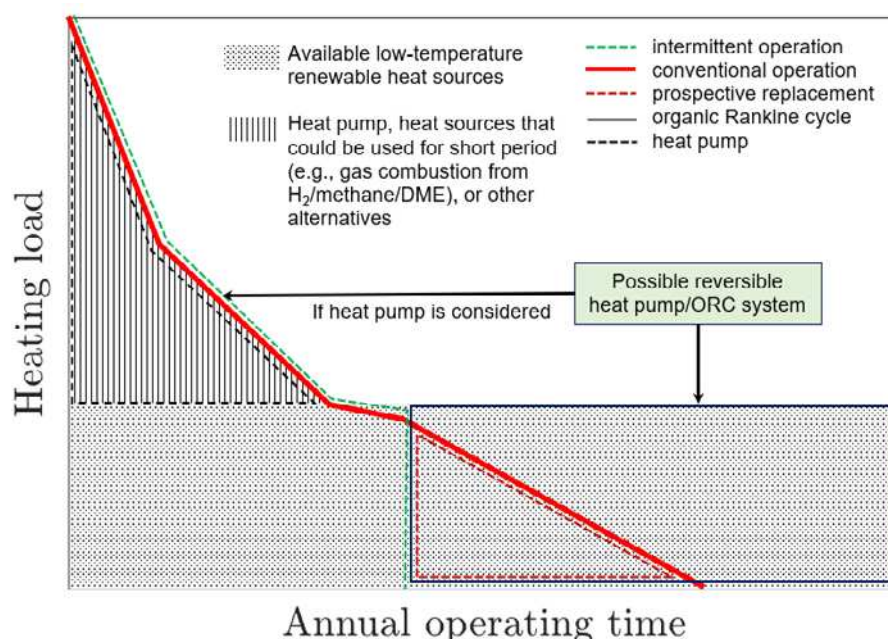


Figure 1: An illustration of an operating system for a case

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.

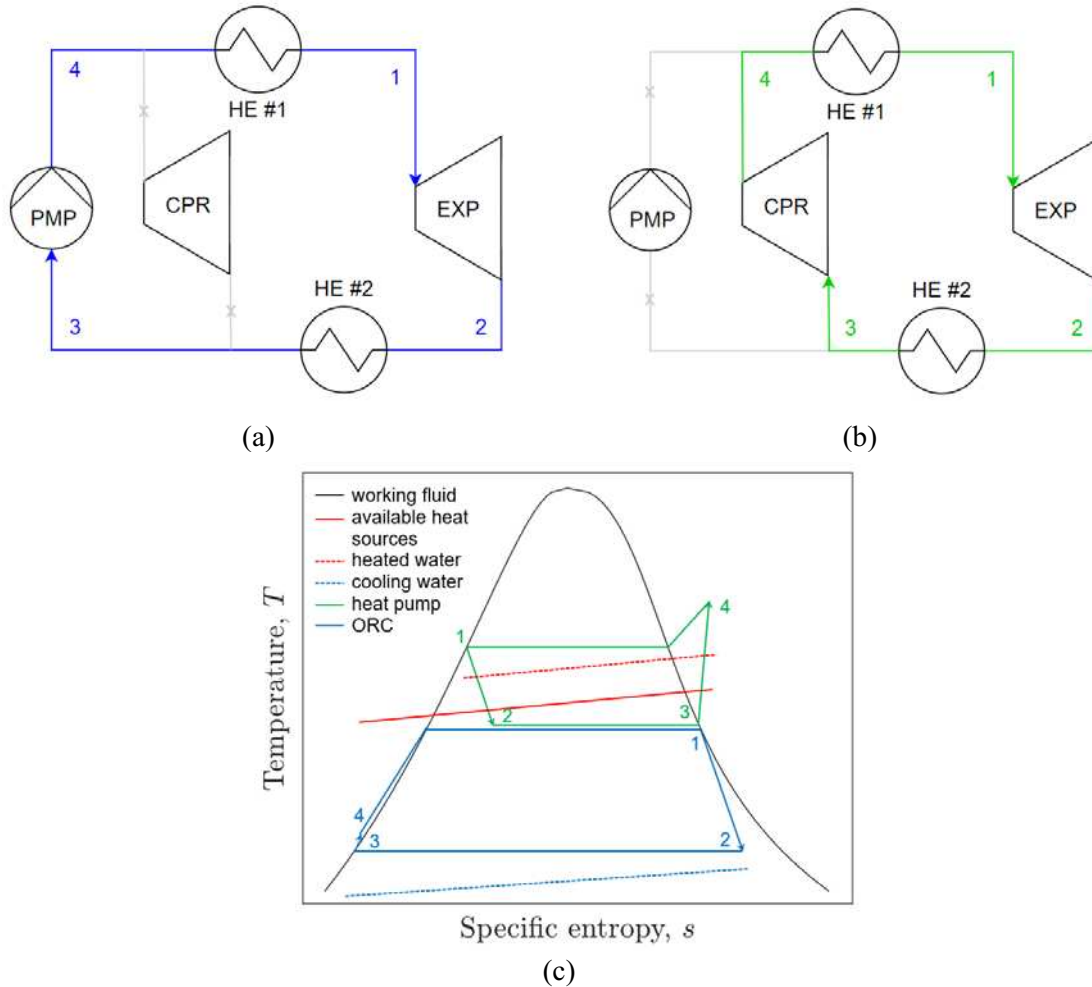


Figure 2: A novel reversible heat pump-organic Rankine cycle (RHPORC) (a) in ORC mode, (b) in heat pump mode, and (c) its thermodynamic process in T - s diagram, where HE, EXP, PMP, CPR describe as the heat exchanger, expander, pump, and compressor, respectively.

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.

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

$$\dot{Q} + \sum \dot{m}_{in} h_{in} = P + \sum \dot{m}_{out} h_{out} \quad (2)$$

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	$h_{ORC.1} - h_{ORC.4}$	$h_{HP.4} - h_{HP.1}$	$\dot{m}_{wf}$	$\dot{Q}_{ORC,HE1},$ $\dot{Q}_{HP,HE1}$
Expander	$h_{ORC.1} - h_{ORC.2}$	$h_{HP.1} - h_{HP.2}$	$\dot{m}_{wf}$	$P_{ORC,EXP},$ $P_{HP,EXP}$
HE #2	$h_{ORC.2} - h_{ORC.3}$	$h_{HP.3} - h_{HP.2}$	$\dot{m}_{wf}$	$\dot{Q}_{ORC,HE2},$ $\dot{Q}_{HP,HE2}$
Pump	$h_{ORC.4} - h_{ORC.3}$	-	$\dot{m}_{wf}$	$P_{ORC,PMP}$
Compressor	-	$h_{HP.4} - h_{HP.3}$	$\dot{m}_{wf}$	$P_{HP,CPR}$

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.

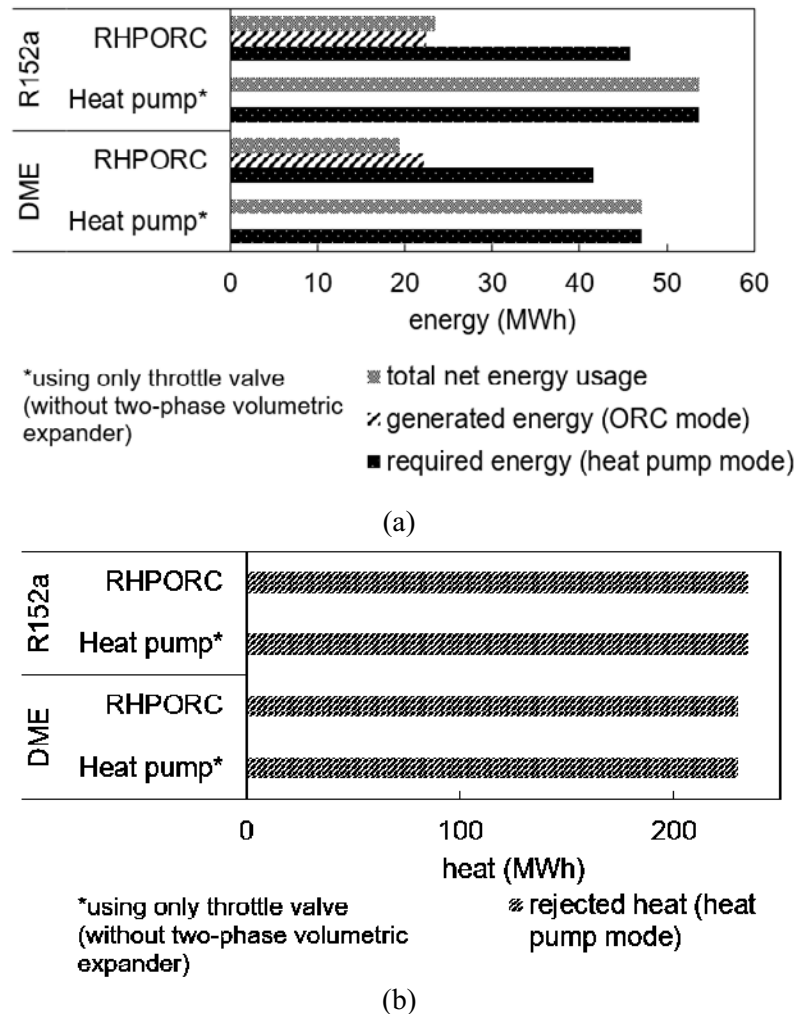


Figure 3: The obtained result in (a) required and produced energy (both heat pump and ORC mode), and (b) the rejected heat (heat pump mode)

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.