

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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(coordinadores)

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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 Schifflachner	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

ASSESSMENT OF HIGH TEMPERATURE HEAT PUMP LAYOUTS EQUIPPED WITH A BLADELESS TURBOEXPANDER

Matteo Passalacqua^{1,*}, Simone Maccarini¹, Stefano Barberis¹, Alberto Traverso¹

¹*Thermochemical Power Group, University of Genova, Via Montallegro 1, 16145 Genova, Italy*

*Corresponding Author: matteo.passalacqua@edu.unige.it

ABSTRACT

Efficient and resilient reverse cycles at MW-scale are needed in industry and energy communities for pursuing the ambitious targets of electrification of industrial processes and thermal generation via renewable power.

This work evaluates the optimal thermodynamic performance features of heat pump cycles comparing conventional layouts with those adopting a Tesla turboexpander, for recovering pressure drop in high temperature applications. The paper focuses on n-pentane (R601), a natural refrigerant, being a favorable substitute of synthetic refrigerants thanks to its low global warming potential (GWP) and adequate thermophysical properties that could allow to reach high temperature thermal outputs ($>150^{\circ}\text{C}$), thus, being suitable for some specific industrial processes. Tesla or bladeless turboexpanders are a promising technology for small volumetric flows and two-phase fluids, featuring low sensitivity to downscaling effects, while retaining high rotor efficiency, which is being investigated for energy-harvesting solutions. The benefit of introducing such expansion device in place of a conventional lamination valve is assessed, in different layout configurations. Simulations were conducted using an improved version of WTEMP-EVO modeling tool, proprietary to University of Genoa.

Results show that the use of Tesla expander improves significantly the overall thermal efficiency in terms of coefficient of performance (COP), thanks to power recovered, depending on the cycle layout.

723

1 INTRODUCTION

The continuous increase of GHG emissions, in particular carbon dioxide that reached a world record in 2022, is encouraging many sectors to adopt new strategies to reduce emissions. Transport, buildings, and industry are the most relevant sectors in terms of final energy consumption, about 2.9 Gtoe each for a total of 60% (IPCC, 2021).

The course of action to abate pollutant substances and GHG emission includes the electrification of heating systems, both industrial and DHNs, which together account for roughly 30% the total emission (IPCC, 2021). However, a benefit from electrification is only obtained if electricity is produced mostly from renewable sources (e.g., solar photovoltaic, concentrated solar power, wind power, hydro, biomass) or carbon-free energy carriers (green hydrogen and green ammonia).

From this point of view, heat pumps are a promising solution. The latest research has focused mainly on three aspects of heat pump plants, namely plant design and machinery optimization, expander introduction, high temperature heat pumps (HTHP) applications and the use of low-GWP natural refrigerants. Recent literature contains numerous studies on heat pumps performance assessment and the replacement of inefficient heating systems with such technology (Adamson et al., 2022) (Chen et al., 2022) (Pan et al., 2021) (Dai et al., 2020) (Jibran et al., 2022).. Working fluids for reverse cycles typically feature high specific heat, high latent heat of vaporization. Halogenated hydrocarbons, such as hydrofluorocarbons (HFCs) and hydrochlorofluorocarbons (HCFCs) are employed at present in many heat pump plants. In accordance with Montreal Protocol (Montreal Protocol, 1987), Kyoto Protocol (Kyoto Protocol, 1997) and the successive Kigali Amendment (Kigali Amendment, 2019) there is an evident need for reducing their usage.

Organic working fluids are a promising alternative to synthetic refrigerants since they have low GWPs while showing comparable thermophysical properties. Besides, some of them allow to achieve high heat sink temperatures thanks to their high critical temperature, interesting for a variety of different industrial application. The recent scientific research focused on natural and low-GWP refrigerants performance (Meinel, Wieland and Spliethoff, 2014) (Kumar Saini et al., 2021) as well as comparative reviews (Bamigbetan et al., 2017) (Frate, Ferrari and Desideri, 2019). A promising example is n-pentane (R601): in accordance with several literature sources (Arpagaus et al., 2018) (Wu et al., 2020), with the relevant exception of water (R718), it has the highest expected COP in the typical temperature range of HTHPs. Some authors (Arpagaus et al., 2018) perform a widespread analysis on several heat pump working fluids, including n-pentane, to evaluate the most suitable ones for high heat sink temperatures. They found that such hydrocarbon is outperformed in terms of optimal temperature range by water and R1336mzz(Z) only. Their results show that R601 is among the most efficient fluids in the range 130-160°C of heat sink temperatures, topping out at a COP of 3.27 for a temperature lift of 70 K. Other authors (Sulaiman et al., 2022) compare different low-GWP refrigerants for HTHP application, showing that R601 has 4% to 18% lower power consumption compared to R245fa. Besides, TEWI for R601 is around 27% lower. Very little literature is available specifically on n-pentane heat pumps. In an old work (Yamazaki and Kubo, 1985), researchers evaluated a 400 kW R601 layout supplying steam at 130°C from waste heat at 90°C. They obtained a COP of 4.5 for source and sink temperatures of 80°C and 135°C, respectively.

The introduction of a dynamic expander in reverse cycles as an energy harvesting device is covered in literature (Zhang et al., 2013) (Nickl et al., 2005) and the performance improvements are registered between 10% and 30% with respect to the base cycle, depending on the layout characteristics (Murthy et al., 2019). Multidisc bladeless friction turboexpanders, also known as Tesla turbines (Tesla, 1913), represent a promising technology as small-scale machinery due to their low sensitivity to downscaling effects, retaining high rotor efficiency. Some authors performed a systematic loss characterization (Renuke et al., 2022), showing that the largest contributions reside in stator-rotor interaction (40%) and ventilation (15%) losses, followed by leakages. Nowadays, its ability to handle low volumetric flows, including two-phase fluids, may pave the way towards Tesla expander adoption in heat pumps as COP booster. In general, this paper aims to widen the knowledge on such an innovative and effective solution to emissions reduction.

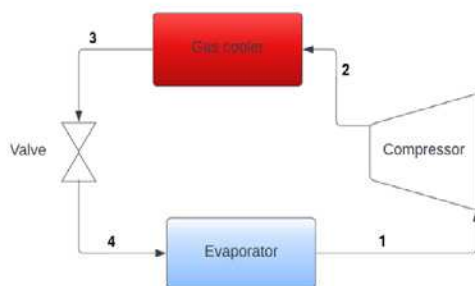
724

2 METHODS

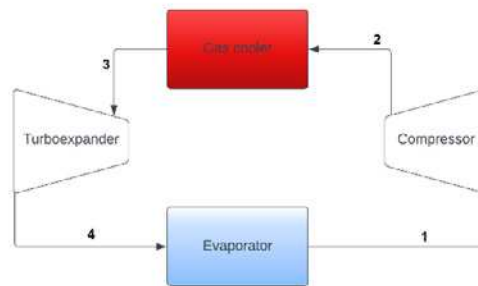
2.1 Layouts analysed

This work assesses different layouts of n-pentane reverse cycles, firstly comparing performance of simple expansion cycle with a novel layout featuring a Tesla turboexpander, and secondly evaluating to what extent two stage compression is beneficial.

Figures 1a-1d describe the investigated layouts: for each of them, models of physical components are created and interfaced with each other to assemble complete cycles.



a)



b)

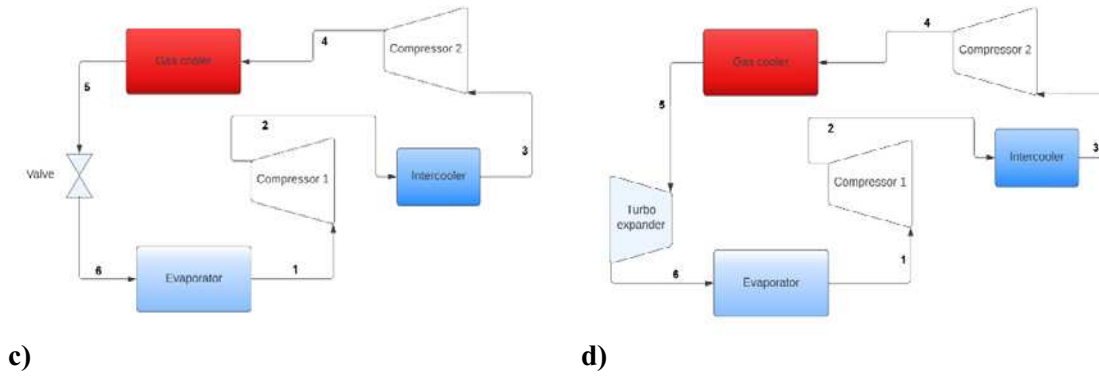


Figure 1a-1d – Schematics of investigated layouts

2.2 Thermodynamic Modelling

This section describes the underlying principles behind the M physical component models constituting the system. The simulation program WTEMP-EVO has been devised to assess and enhance the techno-economic effectiveness of various cycle arrangements and can evaluate several pure fluids with a two-phase or real-gas nature via the utilization of CoolProp (Bell et al., 2014) thermodynamic libraries. This is, in essence, an expansion of WTEMP (Traverso et al., 2004) retaining its modular approach, implying that every component is depicted by a subroutine that calculates parameters based solely on basic thermal evaluations performed within each component, independently of the other constituents. This numerical approach permits the components to be interlinked to obtain the evaluation of any preferred layout. Most component models are lumped representations of real components, with the exception of heat exchangers, which are modelled as 1D components, discretized in 30 computation sections. All components are adiabatic, thus, heat losses towards the environment are neglected.

The compressor reproduces the real component in the plant configuration. Equation (1) reports the definition of polytropic efficiency used in this work for such component. Here, β is the compression ratio, k is the specific heat ratio ($k = c_p/c_v$) and m the exponent of the polytropic transformation. Equation (2) highlights the link between isentropic efficiency and polytropic exponent.

$$\eta_{pol} = \frac{m}{m-1} \cdot \frac{k-1}{k}, \quad (1)$$

$$\eta_c = \frac{1 - \beta^{\frac{k-1}{k}}}{1 - \beta^{\frac{m-1}{m}}} \quad (2)$$

$$h_{out,turb} = h_{in,turb} - (h_{in,turb} - h_{out,s,turb}) \cdot \eta_{s,turb} \quad (3)$$

The turboexpander operates an expansion of the working fluid, generating power at the shaft. This component was assessed by means of equation (3).

The modelling of the expansion valve simply considers an isoenthalpic process between inlet and outlet. The heat exchanger model refers to a shell and tube heat exchanger. The modeling is based on a counter-flow rationale, with the user setting a primary temperature or quality and other parameters such as approach, pinch point temperature difference, and pressure losses. The results of the thermodynamic cycle are then used to determine the geometrical characteristics of the heat exchanger, for which inputs include the velocities of the working and source fluids (u_{fluid} and u_{source}), as well as the internal and external diameters of the pipes (D_{int} and D_{ext}). The heat transfer is computed by use of the ε -NTU criterion, as suggested by notable works (Incropera et al., 2010).

The heat exchanger is discretized into a number of cells ($N=30$ for this work) assuming a constant overall heat transfer coefficient for each cell. The convective heat transfer coefficient is calculated for each cell. The product UA is then calculated by assessing the effectiveness ε for each cell. This involves

assuming equal thermal power exchange for each cell and comparing the actual enthalpy drop of the fluid to the enthalpy drop experienced by the fluid with the lowest heat capacity. The heat transfer surface area is then determined for each cell and summed up to calculate the total surface area of the heat exchanger. It should be noted that thermal conduction along the axial coordinate within the piping material is disregarded in the analysis.

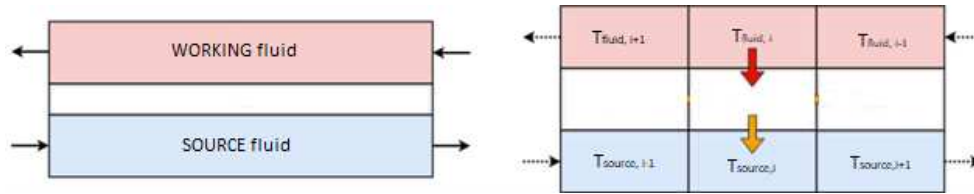


Figure 2: Scheme of counter-flow heat exchanger (cooler)

3 SIMULATION AND RESULTS

3.1 Model Inputs and Constraints

This section describes the model inputs and main constraints. A size of 1 MW_{heat} heating power was chosen as a reference of a sizeable heat pump plant. Table 1 contains the boundary conditions and the general assumptions for each component of the cycle.

Table 1: Boundary conditions and general assumptions

BCs and General Assumptions	
Working fluid	R601
Reference size (Q_{heat})	1 MW _{heat}
Heat exchanger pressure loss	3%
Thermal loss towards ambient	Neglected
Max compressor outlet temperature	180 °C
ΔT superheating (compressor inlet)	50 °C
ΔT subcooling (expander inlet)	30 °C
Condensation pressure (reference)	20 bar
Evaporation pressure (reference)	0.8 bar
Minimum ΔT at HXs	5 K
Mechanical efficiency	0.85
Electrical efficiency	0.9
Compressor polytropic efficiency	0.91
Tesla turbine isentropic efficiency	0.44

It is worth noting that a polytropic compressor efficiency was assumed, according to the assumptions in Table 1. In addition, a maximum temperature of the cycle, that is the compressor outlet temperature, was chosen (Table 1). The justification for this choice is two-fold. On the one hand, high temperatures lead to thermal decomposition of the compressor lubricant, which should be avoided. On the other hand, operation near the critical temperature of R601 (196°C) should be avoided for thermodynamic reasons, such as high variability of the specific heat around the critical point. In addition, such temperature is adequate to ensure sufficient heat transfer even at very high heat sink temperatures. This choice is in line with previous studies (Frate, Ferrari and Desideri, 2019) (Ommen et al., 2015).

3.2 Parametric analysis

The COP is defined as usual for heat pumps, that is, by the following equations:

$$COP_{HP} = \frac{\dot{Q}_{heat}}{\dot{W}_{elect}} \quad (3)$$

A parametric analysis exploring different key parameters was conducted, both for the simple cycle (Figures 3a-3c) and for the Tesla modified cycle (Figures 4a-4c).

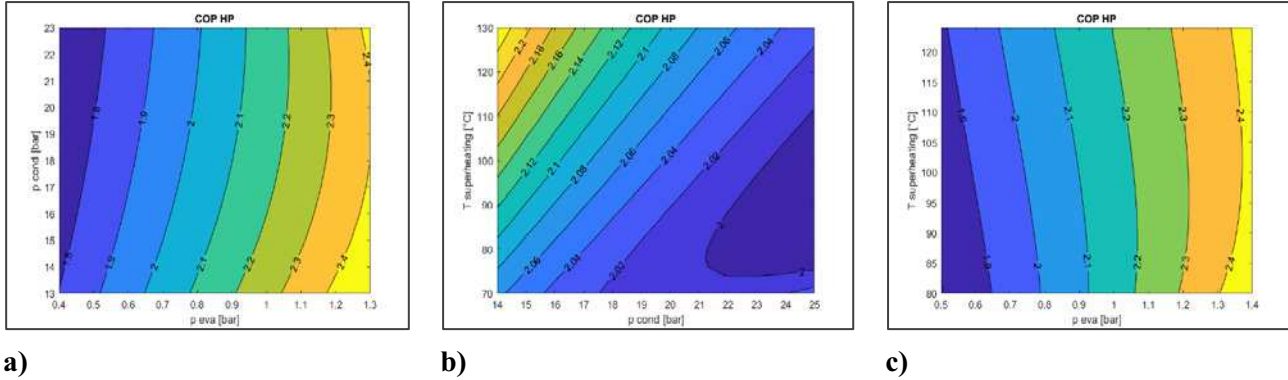


Figure 3a-3c: COP sensitivity against a) p_{cond}/p_{eva} , b) T_{sh}/p_{cond} and c) T_{sh}/p_{eva} for simple cycle

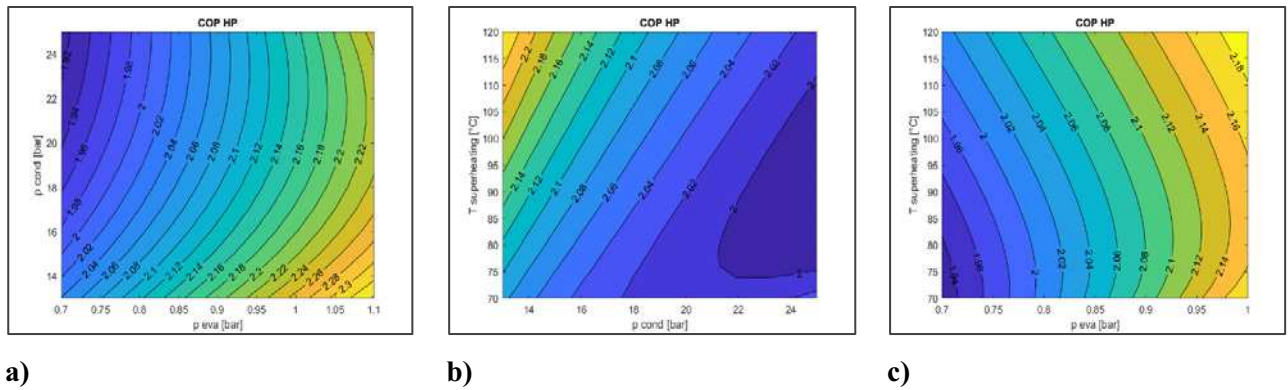


Figure 4a-4c: COP sensitivity against a) p_{cond}/p_{eva} , b) T_{sh}/p_{cond} and c) T_{sh}/p_{eva} for Tesla cycle

Figure 3a demonstrates that COP of the heat pump is scarcely sensitive to condensation pressure, while highly depends on evaporation pressure. Figure 3b depicts an increasing heat pump performance with increasing superheating temperature (i.e., compressor inlet temperature) at low condensation pressures, and Figure 3c show that evaporation pressure have a negligible influence on the COP value. For the Tesla modified cycle, trends depicted are similar, with performance values varying less but in accordance with a narrower pressure range on horizontal axis.

It should be noted that the superheating temperatures are consistently higher than the saturation temperatures at evaporating pressures, confirming that dry refrigerants require high degree of superheating before compressor inlet. In addition, dry refrigerant may not benefit from two-stage compression, or the efficiency gain is very marginal, as shown in previous literature (Meinel, Wieland and Spliethoff, 2014).

Figures 5a to 5c display the required compressor thermodynamic power. With reference to equation (4), the trends are in line with the COP plots.

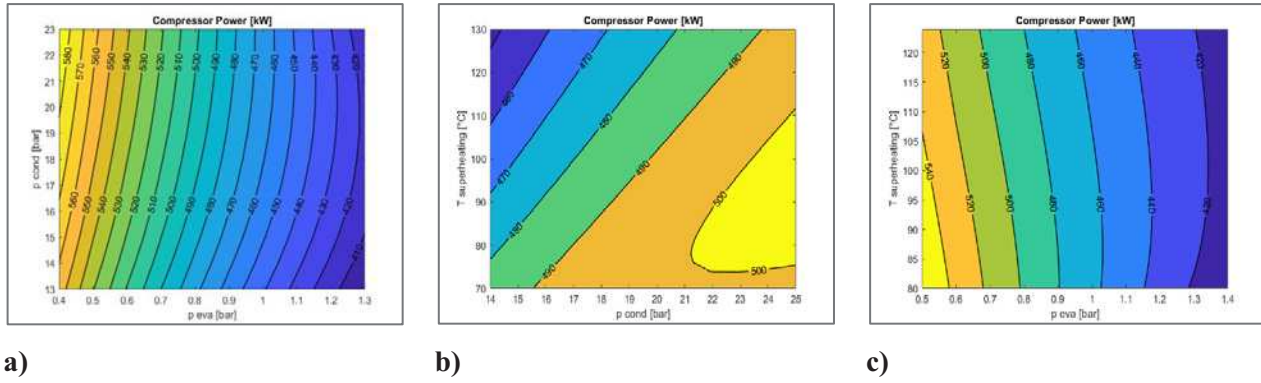


Figure 5a-5c: Compressor power against a) $p_{\text{cond}}/p_{\text{eva}}$, b) $T_{\text{sh}}/p_{\text{cond}}$ and c) $T_{\text{sh}}/p_{\text{eva}}$

With the purpose of addressing energy harvesting, the available expansion power for the Tesla expander is depicted in Figures 6a-6c. It may be observed that such power is slightly dependent on condensation pressure, while increases with decreasing evaporation pressure and superheating temperature.

Figure 7 highlights the COP improvement for three values of evaporation pressure, assuming constant condensation pressure (20 bar). The percentage difference is defined as the difference between Tesla cycle COP and simple cycle COP, divided by the simple cycle COP. The evaporation pressures reported in Figure 7 correspond to R601 saturation temperatures of 16.8 °C, 29.8 °C and 35.7 °C, respectively.

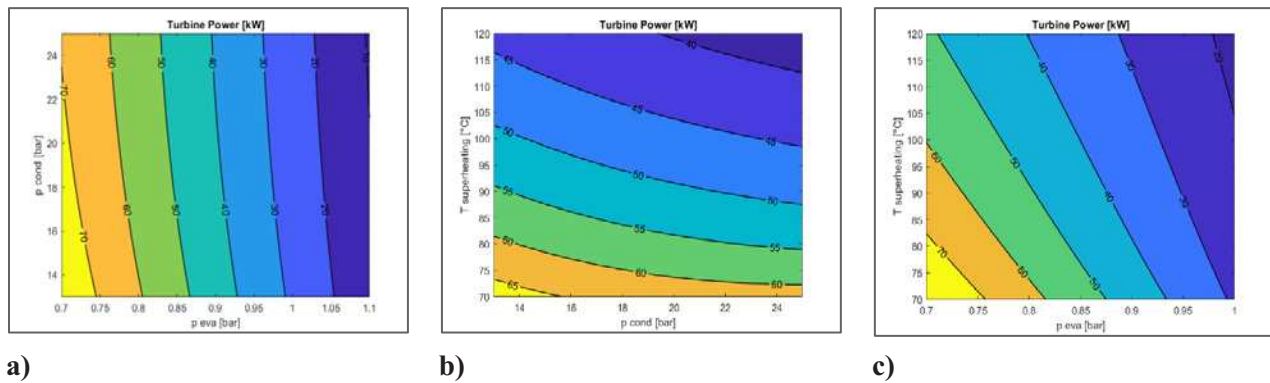


Figure 6a-6c: Tesla expander available power against a) $p_{\text{cond}}/p_{\text{eva}}$, b) $T_{\text{sh}}/p_{\text{cond}}$ and c) $T_{\text{sh}}/p_{\text{eva}}$

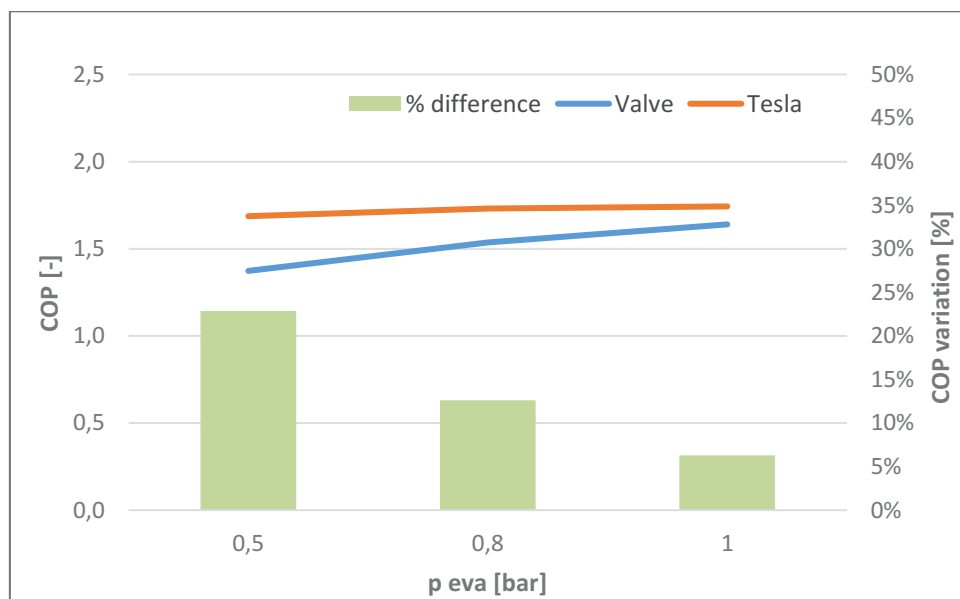


Figure 7: COP comparison between simple and Tesla modified cycle ($p_{\text{cond}} = 20$ bar)

4 PROPOSED CASE STUDY

Despite being a very promising energy recovery option, low-temperature waste heat has major challenges associated with its recovery. Moreover, heat pump performance is always reduced when heat upgrade requires high temperature lifts. To further improve the knowledge of HTHP technology, a real industrial case study is presented below. These results might indicate the suitability of HTHP for various industrial applications and justify further detailed research and experimental activities.

4.1 Case Study Description

A manufacturer of laminate products for the building and furniture industry disposes of a hot water tank from the pressing process, that is to be evaluated as a thermal source for the production of pressurized hot water at 160°C and 20 bar for a different process.

Since a consistent temperature glide is involved (around 100 °C, Table 2), R601 was evaluated due to its favourable properties. Machinery efficiencies are the same reported in Table 1.

Table 2: Boundary conditions for the case study

BCs and General Assumptions	
Source water inlet temperature	≈ 60 °C
Source water outlet temperature	≈ 35 °C
Process water inlet temperature	≈ 120 °C
Process water outlet temperature	160 °C

4.2 Case Study Results

Table 3 delivers briefly the results of the simulation for the aforementioned industrial case study.

Table 3: Performance comparison for R601 HTHP according to the case study

COP comparison	
COP simple cycle	1.54
COP Tesla modified cycle	1.73

As expected, the heat pump performance benefits from the presence of a Tesla expander by matter of 13%, in good accordance with numerous literature sources. To complete the analysis, Figures 8a-8b report p-h charts for the two cases and Figures 9a and 9b show examples of T-Q chart along the discretization coordinate x relative to two relevant heat exchange processes for the case study conditions. Figure 8a refers to the de-superheating process of the refrigerant prior to its condensation.

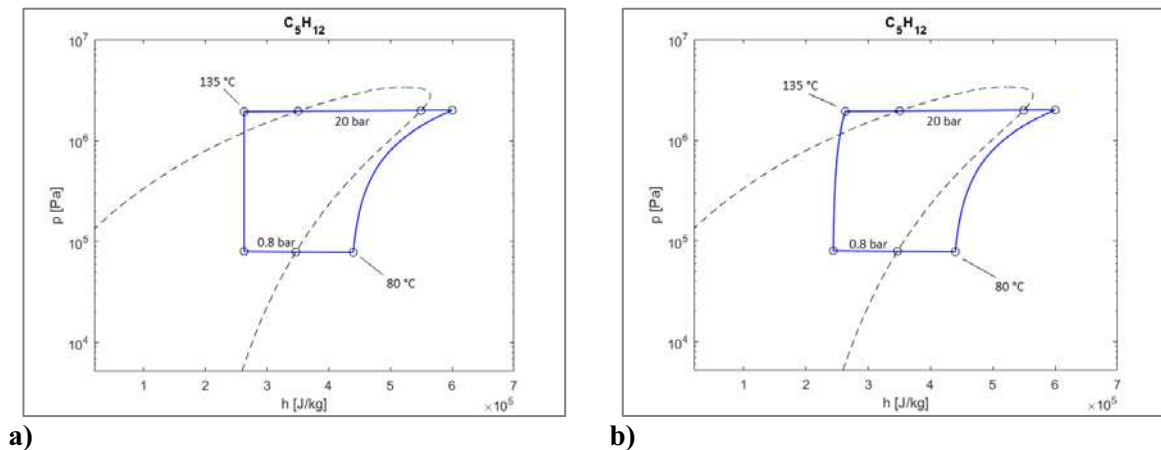
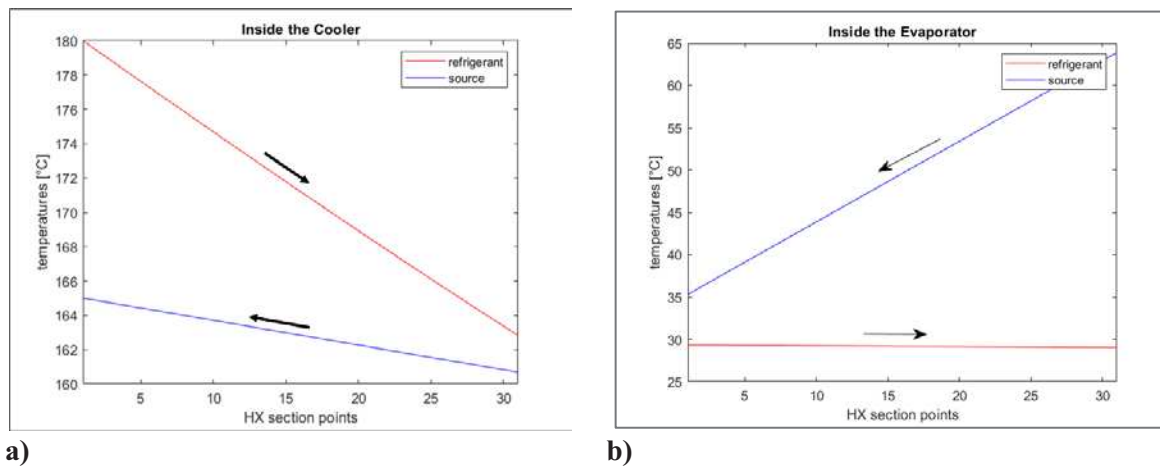


Figure 8a-8b: Semi-logarithmic p-h comparison for R601 HTHP according to the case study**Figure 9a-9b:** T-x chart for the a) de-superheating and b) evaporation according to the case study (x represents the axial coordinate of the external heat transfer fluid)

5 CONCLUSIONS

In this paper, techno performance of n-pentane HTHP have been analysed. A MW-sized plant was investigated as reference for an industrial application. The updated WTEMP-EVO software was adopted to model and simulate the cycle. Performance was assessed under on-design conditions and a sensitivity analysis on relevant parameters was performed.

The results confirm the promising use of expanders to harvest a significant amount of energy and to improve the COP of the cycle. Optimal conditions for turboexpander cycle are obtained in a narrower range of operating conditions. A 13% COP improvement was achieved in the industrial case study simulation. In addition, Tesla turbines have further advantages concerning almost size-independent efficiency and reduced cost with respect to traditional turboexpanders, and potentially can better manage two-phase flows, without the risk of erosion. Dual stage compression cycles were not assessed, since R601 is a dry refrigerant and, having a very sloped saturation curve, compression “follows” that curve quite solidly (Figures 6a-6b), so fluid intercooling may not improve significantly cycle performance, considering also the added plant complexity and costs.

NOMENCLATURE

COP	Coefficient of Performance
GHG	Greenhouse Gas
GWP	Global Warming Potential
HP	Heat Pump
HTHP	High Temperature Heat Pump
IPCC	Intergovernmental Panel on Climate Change
NTU	Number of Transfer Units
TEWI	Total Equivalent Warming Impact
UNFCC	United Nations Framework Convention on Climate Change

Symbols

P	Pressure	[bar]
T	Temperature	[°C, K]
h	Enthalpy	[kJ/kg]
s	Entropy	[kJ/kg K]

m	Mass flow	[kg/s]
x	HX discretization coordinate	[-]
ΔT	Temperature gradient	[K]
β	Pressure ratio	[-]
k	Heat capacity ratio	[-]

Subscript

in	Inlet
out	Outlet
int	Internal
ext	External
elect	Electrical
s	Isentropic
pol	Polytropic
cond	condenser
eva	evaporator
sh	Superheating
subc	Subcooling
fluid	Working fluid
source	Source fluid
heat	Heating power

REFERENCES

- Adamson, K.M, et al., 2022, "High-temperature and transcritical heat pump cycles and advancements: A review,," *Renewable and Sustainable Energy Reviews*.
- Arpagaus, C., Bless, F., Uhlmann, M., Schiffmann, J. and Bertsch, S., 2018, High temperature heat pumps: Market overview, state of the art, research status, refrigerants, and application potentials, *Energy* 152, 985-1010.
- Bamigbetan, O., Trygve, M.E., Neska, P., and Bantle, M., 2017, Review of vapour compression heat pumps for high temperature heating using natural working fluid, *International Journal of Refrigeration* 80, 197-211.
- Bell, I., Wronski, J., Quoilin, S., and Lemort, V., 2014, Pure and pseudo-pure fluid thermophysical property evaluation and the open-source thermophysical property library CoolProp, *Ind Eng Chem Res* 53, 2498-2508.
- Bergman, T.L., Lavine, A., Incropera, F. and DeWitt, D., 2018, *Fundamentals of Heat and Mass Transfer, 8th Edition*. Wiley & Sons.
- Chen, Y., Standl, P., Weiker, S., and Gaderer, M., 2022, A general approach to integrating compression heat pumps into biomass heating networks for heat recovery, *Applied Energy* 310.
- Dai, B., Qi, H., Dou, W., Liu, S., Zhong, D., Yang, H., Nian, V. and Hao, Y., 2020, Life cycle energy, emissions and cost evaluation of CO₂ air source heat pump system to replace traditional heating methods for residential heating in China: System configurations, *Energy Conversion and Management* 218.
- European Fluorocarbons Technical Committee, <https://www.fluorocarbons.org/environment/climate-change/global-warming-potential/> (accessed November 30, 2022).
- Ferrando, M., Renuke, A., Traverso, A. and Sishtla, V., 2021, A new design method for two-phase nozzles in high efficiency heat pumps, *International Journal of Refrigeration*, 148-156.
- Frate, G.F, Ferrari, L. and Desideri, U., 2019, Analysis of suitability ranges of high temperature heat pump working fluids, *Applied Thermal Engineering*, 628-640.
- IPCC, Sixth Report Assessment (AR6), Geneva (CH), 2021.
- Jibrán, M., Zuberi, S., Hasanbeigi, A. and Morrow, W., 2022, Bottom-up assessment of industrial heat pump applications in U.S. Food manufacturing, *Energy Conversion and Management* 272.

- Kigali Amendment, Kigali, 2019.
- Kyoto Protocol, Kyoto, 1997.
- Meinel, D, Wieland, C. and Spliethoff, H., 2014, Effect and comparison of different working fluids on a two-stage ORC concept, *Applied Thermal Engineering*, 246-253.
- Montreal Protocol, Montreal, 1987.
- Murthy, A.A, Subiantoro, A., Norris, S., and Fukuta, A., 2019, A review on expanders and their performance in vapour compression refrigeration systems, *International Journal of Refrigeration* 106, 427-446.
- Nickl, J., Will, G., Quack, H., and Kraus, W.E., 2005, Integration of a three-stage expander into a CO₂ refrigeration system, *International Journal of Refrigeration* 28, no. 8, 1219-1224.
- Ommen, T, Jensen, J.K., Markussen, W.B., Reinholdt, L., and Elmegaard, B., 2015, Technical and economic working domains of industrial heat pumps: Part 1 – Single stage vapour compression heat pumps, *International Journal of Refrigeration*, 168-182.
- Pan, M., Zhu, Y., Liang, Y., Lu, F., Zhi, R., and Xiao, G., 2021, Performance assessment of a waste-heat driven CO₂-based combined power and refrigeration cycle for dual-temperature refrigerated truck application, *Energy Conversion and Management* 249, no. 114863
- Renuke, A., Reggio, F., Traverso, A., and Pascenti, M., 2022, Experimental Characterization of Losses in Bladeless Turbine Prototype, *Journal of Engineering for Gas Turbines and Power*, 144.
- Renuke, A., and Traverso, A., 2022, Performance assessment of Tesla expander using Three-Dimensional numerical simulation, *Journal of Engineering for Gas Turbines*, 144, no. 11
- Sarbu, I. 2014, A review on substitution strategy of non-ecological refrigerants from vapour compression-based refrigeration, air-conditioning and heat pump systems, *International Journal of Refrigeration* 46, 123-141.
- Sulaiman, A., Cotter, D.F., Le, X.K., Huang, M.J., and Hewitt, N.J., 2022, Thermodynamic analysis of subcritical high temperature heat pump using low GWP refrigerants: A theoretical evaluation, *Energy Conversion and Management* 268.
- Tesla, N., Turbine. U.S. Patent 1061206, 1913.
- Traverso, A. Reverse cycle machine provided with a turbine. Patent WO2018127445A1
- Traverso, A., A.F Massardo, Cazzola, W. And Lagorio, G., 2004, WIDGET-TEMP: a novel web-based approach for thermoeconomic analysis and optimization of conventional and innovative cycles, *ASME Turbo Expo 2004: Power for Land, Sea, and Air*, 623-631.
- UNFCCC. Paris Agreement, Paris, 2015.
- Westphalen, D., and Dieckmann, J., 2004, Scroll Expander for Carbon Dioxide Air Conditioning Cycles, *International Refrigeration and Air Conditioning Conference*. Purdue, IN (US).
- Wu, D., B Hu, Wang, R.Z., Fan, H., and Wang, R., 2020, The performance comparison of high temperature heat pump among R718 and other refrigerants, *Renewable Energies*, 715-722.
- Yamazaki, T., and Kubo, Y., 1985, Development of a high-temperature heat pump, *IEA Heat Pump Centre Newsletter* 3, no. 4, 18-21.
- Zhang, Z., Yitai M., Li, M., and Li Z., 2013, Recent advances of energy recovery expanders in the transcritical CO₂ refrigeration cycle, *HVAC&R Research* 19, no. 376-384.

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.