David Tomás Sánchez Martínez
Lourdes García Rodríguez
(coordinadores)

Proceedings of the 7th International Seminar on ORC Power Systems

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ORC

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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 Schifflechner, 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 sCO2 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 Schifflechner, 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 CO2 power cycles in Waste Heat Recovery applications
Authors: Hicham Chibli, Matthew Read, Abdulnaser 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 CO2-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, GiampaoloManzolini, Constante Mario Invernizzi, Marco Astolfi 282

ID46 - Thermodynamic analysis of a novel pumped thermal energy storage system with waste heat integration
Authors: Meiyan 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, Abdulnaser Sayma, Martin T. White........ 304

ID51 - Thermodynamic modification of CO2-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 CO2-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 Oliveti, 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 CO2-Plume Geothermal (CPG) Systems for CO2 component manufacturers: opportunities and development needs
Authors: Christopher Schifflechner, 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 Schifflechner, 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 Touliankine, 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 CO2-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 Schifflechner 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 CO2 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 Ziólkowski, 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 Guedez 751

ID142 - Aerodynamic design and numerical analysis of a counter-rotating centrifugal compressor
Authors: Cheikh Brahim Abed, Arthur Leroux 761

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ASSESSMENT OF TRILATERAL ORGANIC RANKINE CYCLE FOR SOLAR APPLICATIONS WITH INNOVATIVE TURBOEXPANDER CONCEPT

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ABSTRACT

Low-temperature solar collectors coupled with thermal energy storage can enable stable and carbon-free energy production. The key issue is to efficiently convert solar energy into electricity without resorting to complex architecture that may hinder the technical and economic feasibility of the entire system. In this work, we propose a fully integrated organic Rankine cycle (ORC) with the solar field and energy storage, targeting 200 kW. The system consists of a single circuit of the selected organic fluid that passes through the solar collectors, the thermocline thermal energy storage, and the ORC unit. The organic fluid remains liquid inside the solar field and the thermal energy storage, leading to a trilateral thermodynamic cycle. Leveraging the thermodynamic behavior of molecularly complex fluids, the radial-inflow turbine expands from saturated liquid to superheated vapor. Following the idea of White (App. Therm. Eng., 192 (2021), 116852), the nozzle cascade expands the two-phase flow mixtures and delivers superheated vapor to the rotating cascade. In this way, the rotor processes dry organic vapors without incurring mechanical damage or suffering from additional losses due to two-phase interactions. Three maximum temperatures are investigated, and each of them entails a different fluid selection to have the liquid-to-vapor expansion through the stator. Preliminary designs of the radial-inflow turbines are carried out by employing a meanline code, validated for single-phase organic-fluid flows, revealing that feasible designs can be obtained. Based on these results, the proposed technology appears feasible and promising on the technical ground.

1 INTRODUCTION

A number of studies have investigated the potential of trilateral (TORC) or partial evaporation organic Rankine cycles (PE-ORC), for improving the total conversion efficiency of ORC (Smith, 1993; White, 2021). The advantage of partial evaporation is related to the reduction of the isothermal heat of vaporization, allowing for a better temperature match between the heat source and the organic fluid, and resulting in higher usage of the energy available from the heat source (Fischer, 2011).

In the context of distributed concentrated-solar power (CSP) applications, the use of TORC was investigated by several authors (see, e.g., Casati et al., 2013; Perusi & Astolfi, 2019) as a solution able to guarantee an easy integration of thermal energy storage (TES) without the need of a heat transfer fluid loop, i.e. the organic fluid also passes through the solar field and is stored directly in the TES. The organic fluid must remain liquid in these components, hence the fluid is liquid before entering the expansion phase. To overcome the issue related to the two-phase expansion, Casati et al. (2013) proposed a throttling valve to accomplish a flashing process, delivering saturated vapor to the turbine.

A possible solution to avoid the throttling valve can be represented by positive-displacement machines (Smoth, 1996; Astolfi, 2015), as experimental tests proved their excellent capabilities in managing multi-phase mixtures (Henrik & Per, 2013). Nonetheless, the achievable expansion ratio is limited by the built-in volume ratio of the machine. Multi-stage arrangements can extend the overall volume ratio, but even so, the maximum value is around 20 (Read, 2017), thus restricting the applicability of twin-screw turbines only to low-temperature applications (~ 373 K). To circumvent this limit, thus enabling the uptake of the technology for temperatures up to 523 K, turboexpanders seem the only viable solution. This collides with the lack of turbine designs capable of handling two-phase mixtures efficiently (additional loss due to two-phase interaction) and reliably (droplets impinging rotating cascades).

A remedy can be offered by the peculiar thermodynamics of molecularly complex organic fluids, for which the flashing process may lead the whole liquid fraction to evaporate into superheated vapor (Lai & Fischer, 2012). This concept, introduced by Elliott (1982) and referred to as the wet-to-dry cycle, has been recently revamped by White (2021). Leveraging such fluid characteristics, White (2021) conceived a turbomachinery (estimated efficiency > 85%) in which the nozzle cascade expands the two-phase flow and delivers superheated vapor to the rotating cascade.

In this work, the idea of White (2021) for the turbine concept is adopted to enable a TORC directly coupled with the solar field and TES, thus removing the need for the throttling valve and the flashing unit. To this aim, a number of fluids are preliminarily envisaged, and the effects on the plant and turbine design are highlighted.

2 SYSTEM DESCRIPTION

The direct solar TORC concept is based on the coupling of a CSP solar field (i.e., parabolic trough or linear Fresnel reflectors), a TES, and a two-phase direct expansion ORC. In particular, the working fluid, entering the solar field as sub-cooled liquid, is heated by the concentrated solar radiation till reaching saturated-liquid condition. Since the hot and cold fluid are both in the liquid state, it is possible to directly store thermal energy in a single-tank thermocline (i.e., packed bed with solid filler) without the need for a different storage media, thus allowing the reduction of the cost associated with a heat transfer fluid loop. The saturated liquid is directly expanded in the turbine (Exp) and the discharged superheated steam enters the regenerator (Reg) to pre-heat the working fluid before entering the solar field. Figure 1 shows the layout of the direct solar TORC considered. 141

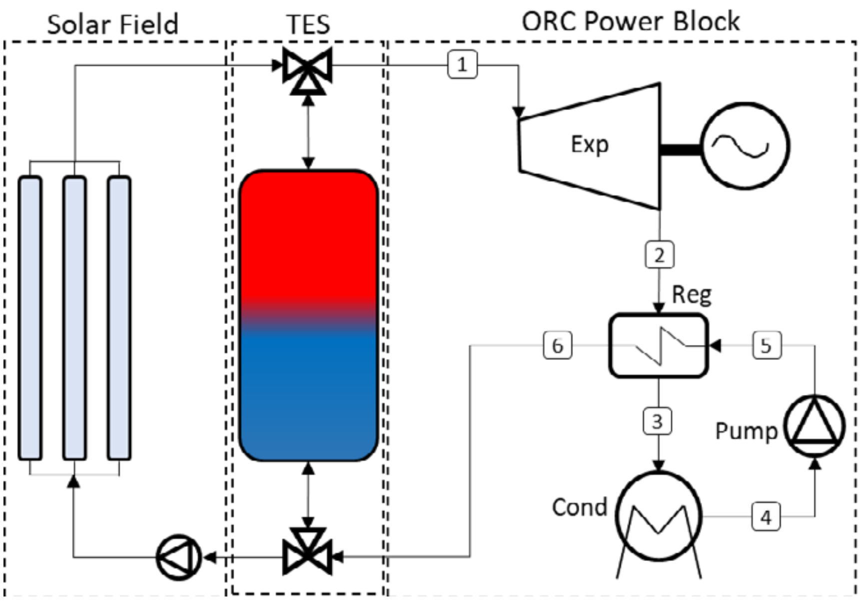

Figure 1: Plant layout. Exp: Radial-inflow turbine. Cond: Condenser. Reg: Regenerator. TES: Thermal Energy Storage.

The electric power output is set to 200 kW; in particular, small-scale CSP plants are recognized as a viable solution to foster technology development thanks to easier land availability and a reduction of bankability issues (Skumanich, 2011). As underlined by Rohani et al. (2021), limited water resources in potentially suitable locations (i.e., semi-desertic areas) point towards the adoption of an air-cooled condenser. As per the system model, the different investigated designs are based on a set of common assumptions as summarized in Table 1 (Casati et al., 2013; Perusi & Astolfi, 2019).

Table 1: Main assumptions considered for the simulation of the ORC system.

Cycle						Pressure drops		
$\dot{W}_{net}$ [kW]	η_{pump}	η_{m-e}	η_{aux}	$\Delta T_{pp,rec}[K]$	x_1	$\Delta P_{sf}[bar]$	$\Delta P/P_{in,reg}$ Liq - vap	$\Delta P/P_{in,cond}$
200.0	0.75	0.97	0.95	5.0	0	1.0	0.03 - 0.02	0.02

In this work, the aim is to assess the feasibility of the system, rather than targeting a detailed system design and optimization. It follows that the focus is on the expander as it is the sole component that is not off-the-shelf. On the contrary, the solar field and heat exchangers employed in this solution are commercially available, while the single-tank TES is a well-proven solution that has been already tested in a real operating environment (Pelay et al. 2017). Therefore, the maximum temperature is imposed as a boundary condition, and a complete model for the solar field is avoided in this preliminary feasibility study. Only cycle efficiency will be discussed, instead of sun-to-electrical (global) efficiency. For the same reason, the pressure drops in the solar collectors (ΔP_{sf}) are assumed constant. Under these assumptions, the points of the thermodynamic cycle can be determined straightforwardly as for a simple recuperative ORC.

2.1 Fluid Screening

142

A number of molecularly complex organic fluids are preliminarily considered, which can potentially enable a complete liquid vaporization within an adiabatic stator. As previously highlighted, the expansion starts from saturated liquid to avoid a two-phase mixture in the solar field and thermal energy storage system, thus enabling a relevant simplification of the plant layout. The constraint of the saturated liquid condition is the main difference from the findings of White (2021), who instead considered the inlet vapor quality as a free parameter to optimize the second-law efficiency of the cycle. As a result of this additional constraint, the number of organic fluids that can accomplish the complete vaporization in the stator is likely reduced. Moreover, as the organic fluid also passes through the solar collector, the analysis is limited to non-flammable fluids. The candidate fluids are linear siloxanes (MM, MDM), cyclic siloxanes (D4, D6), and a Novec fluid (NOVEC649).

To assess the feasibility of the candidate fluids, an isentropic expansion is considered from saturated liquid conditions corresponding to the maximum cycle temperature T_{max} up to the condensation pressure P_{cond}. Three maximum temperatures are considered: $423\,K$, $473\,K$, and $523\,K$. As the maximum temperature increases, the cycle efficiency raises as well. A higher maximum temperature, compatible with the thermal degradation of the selected organic fluid, can be obtained by increasing the concentration ratio of the solar collectors (commercial linear absorbers can reach a maximum temperature equal to 660 K). However, this would increase the CAPEX of the system. Therefore, the optimal T_{max} will result from the techno-economic optimization of these two competing effects. In this study, the aim is the technical feasibility, hence more maximum temperatures are analyzed in this phase. Regarding the minimum cycle temperature, which is the condensation temperature, it directly establishes the minimum pressure in the cycle. To avoid extreme sub atmospheric pressures, which complicate the condenser design and maintenance, the condensation temperature is taken as $T_{cond} = \max(316\,K, T_{sat}(P_{cond} = 0.03\,bar))$.

Figure 2 reveals which fluids can theoretically enable a complete liquid vaporization in the stator. The candidate fluid changes with the maximum temperature. In particular, an increase in T_{max} requires a more complex fluid with a higher critical temperature.

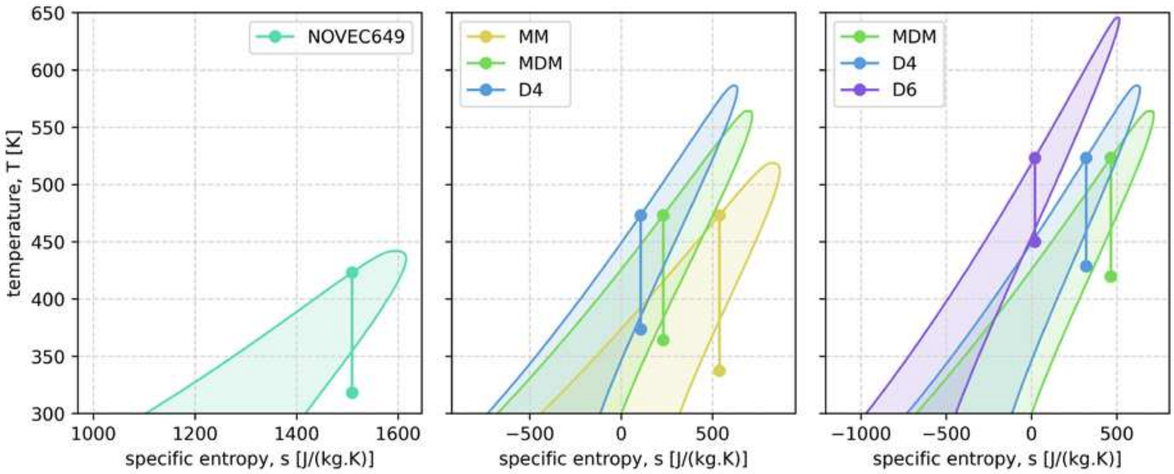

Figure 2: Candidate fluids that can enable a liquid-to-vapor expansion through an isentropic expansion from $P_{sat}(T_{max})$ to $P_{cond} = \max(P_{sat}(T_{cond} = 416\ K), 0.03\ bar)$.
Left: $T_{max} = 423\ K$. Middle: $T_{max} = 473\ K$. Right: $T_{max} = 523\ K$.

3 TURBINE MODEL

The turbine performance and design are carried out with an in-house meanline code (Manfredi et al., 2021). The code was validated against the performance data of seven radial turbines, including radial-inflow turbines for ORC application, by Manfredi et al. (2021). The meanline method is based on the solution of one-dimensional continuity, energy, and momentum equations, complemented with specific correlations for losses. It includes the following components: (i) the nozzle, either of converging or converging-diverging type, (ii) the vaneless interspace, (iii) the rotor, with either radial or backswept blades at the inlet, and (iv) a downstream conical diffuser. The model retrieves the full turbine geometry, comprehensive of nozzle/rotor blade angles, clearances, blade thicknesses, cascade pitches, chords and openings, and it evaluates the average flow quantities and thermodynamic state at each turbine section (1, 3*, 3, 4, 6, 7), identified as in Figure 3. 143

To properly take into account the loss generation mechanisms across each component, a suitable set of empirical models was selected through a loss sensitivity analysis, whose details can be found in Manfredi et al. (2021) together with the resulting optimal set of loss correlations. In a nutshell, the following sources of loss are considered: nozzle passage loss (Glassman, 1976), nozzle trailing-edge loss (Glassman, 1976), friction in the vaneless interspace (Kastner & Bhinder, 1975), rotor passage loss (Baines, 1998), rotor trailing-edge loss (Glassman, 1976), rotor clearance loss (Spraker, 1987), windage loss in the backplate (Daily and Nece, 1960), and kinetic energy loss.

The input parameters to perform the turbine design are the inlet conditions, namely the total pressure, the total temperature, the flow angle, the mass flow rate, and the required pressure ratio. In addition to the system inputs, other design variables, which include several geometrical ratios (i.e., r_{6hub}/r_{6tip}, b_4/r_4, r_1/r_3, and cascade solidities) and a few key dimensionless parameters (flow coefficient, work coefficient), are set based on empirical best practices. The reaction degree is modified to maximize the efficiency while ensuring dry-vapor conditions at the stator outlet, taking a conservative margin from saturation to accommodate potential non-equilibrium effects. For all cases presented afterward, the reaction degree does not exceed the value of 0.3.

The method implements a strategy to handle nozzle choking conditions and three different geometries may be contemporarily investigated: subsonic converging nozzles, converging nozzles in choking conditions with post-expansion, and supersonic converging-diverging nozzles. As the two phases within the stator are considered at the thermodynamic equilibrium, the speed of sound is smaller than their single-phase counterparts, leading to supersonic flows at the stator outlet. Therefore, converging-diverging nozzles are required to handle the supersonic expansion efficiently. The post-expansion ratio in the semi-bladed channel ($3^* \mapsto 3$) is set at 0.92. Finally, the meanline method is not able to handle rotors with supersonic Mach numbers ($M_{w4} > 1$). From a technical ground, supersonic rotors bring additional design challenges and reduced turbine operability (unstarting issues and unique incidence). The turbine efficiency η_{turb}, which is employed in the cycle analysis, is the total-to-static efficiency evaluated at the diffuser outlet.

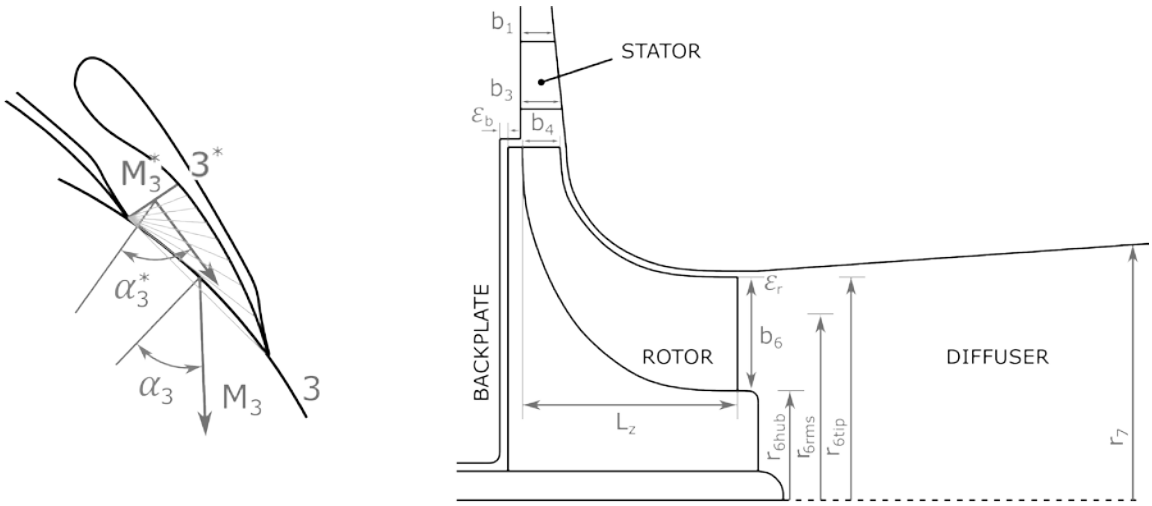

Figure 3: Details of the supersonic post expansion in the converging-diverging stator (left) and meridional channel of the turbine (right) – adapted from Manfredi et al. (2021).

4 RESULTS AND DISCUSSION

In this section, the thermodynamic cycle estimates are discussed alongside the associated turbine design. To integrate the turbine design with the cycle, a first cycle design is run with a constant turbine efficiency ($\eta_{turb} = 0.800$). This first iteration sets the boundary conditions for the turbine design. Once the meanline turbine design is obtained, as well as its isentropic efficiency, the cycle estimates are updated with the new turbine efficiency. A new design would follow due to the mass-flow rate variation to meet the target of 200 kW. However, the deviation is so small that the same turbine design can accommodate the new mass flow rate with negligible variation in efficiency.

Table 2 reports the outcomes of the integrated cycle and turbine analysis. The cycle efficiency increases with the maximum temperature, although such an increase may be hindered by the higher condensation temperature that complies with the technical constraint on the minimum pressure. Such constraint is particularly relevant for cyclic siloxanes, for which the condensation temperature is rather high ($> 348\ K$). A cogenerative exploitation may help compensate for this penalty in electric efficiency, as proposed by Casati et al. (2013).

However, at the highest temperature ($T_{max} = 523\ K$), efficient turbine designs were not found. Although some fluids (i.e., MDM, D4, and D6) can be regarded as potential fluids from a cycle perspective, a number of design issues occur. Cyclic siloxanes require supersonic relative Mach numbers at the rotor inlet to accomplish the expansion, leading to unfeasible meanline turbine design. On the other hand, the MDM turbine can be designed with $M_{w4} < 1$, but the rotor deceleration in the absolute frame of reference is not sufficient to bring M_6 to subsonic values. This would complicate the diffuser design (converging-diverging shape), and there would be two sonic throats (nozzle and diffuser) that would drastically reduce the turbine operability.

Table 2: Main cycle and turbine parameters. Underlined fluid names indicate the most suitable fluids for the corresponding maximum temperatures. Fluids marked with * lead to not feasible turbine designs (cycle efficiency computed with $\eta_{turb} = 80.0\%$).

Fluid	P_{cond} [bar]	T_{cond} [K]	P_{max} [bar]	T_{max} [K]	η_{turb} [%]	η_{cycle} [%]
<u>Novec649</u>	0.88	318	13.15	423	84.7	11.7
<u>MM</u>	0.14	318	9.21	473	85.3	17.0
MDM	0.03	329	3.02	473	85.6	15.7
D4*	0.03	349	1.80	473	n/a	12.7
MDM*	0.03	329	7.48	523	n/a	20.7
D4*	0.03	349	4.86	523	n/a	18.1
D6*	0.03	404	1.13	523	n/a	12.0

The fluids that maximize the cycle efficiency are Novec 649 ($T_{max} = 423\ K$) and MM ($T_{max} = 473\ K$). The cycle thermodynamic transformations and the evolution of static quantities in the turbine are conveniently reported in a temperature-specific entropy ($T - s$) diagram in Figure 4. In the same figure, the meridional channels of the corresponding turbines are also reported.

As displayed in Figure 4(b), all turbine stators complete the fluid vaporization. The pressure at the stator 145
outlet is consistently lower than the saturation pressure along the same isentrope to accommodate potential non-equilibrium effects, which can delay the complete liquid vaporization (White, 2022).

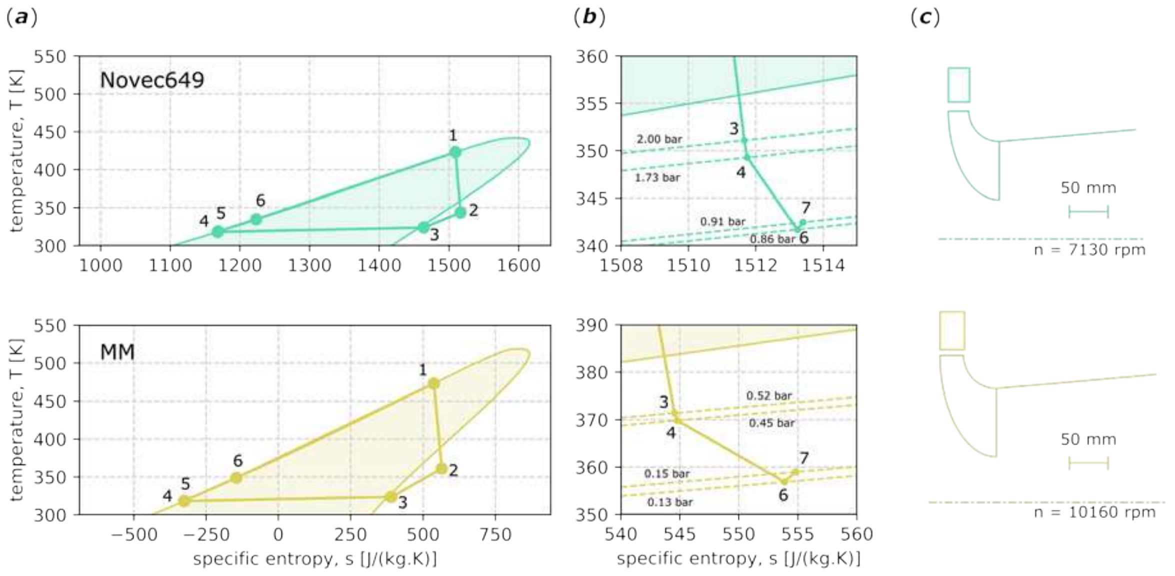

Figure 4: (a) Thermodynamic transformations of feasible TORCs for different temperature levels – see Figure 1 for point nomenclature. (b) Static thermodynamic states in the turbine – see Figure 3 for point nomenclature. (c) Meridional channel of corresponding radial-inflow turbines.

The Novec649 and MM turbine are similar in terms of dimensions. As the MM turbine has to provide a three-times larger specific work, this is accomplished by increasing the centripetal action via the rotational speed, which raises to 10 000 rpm and is still easily achievable by means of gearboxes available in the market. The stator deals with most of the expansion, delivering an absolute supersonic flow at the rotor, which becomes subsonic in the relative frame of reference. As the two-phase mixture is considered at thermodynamic equilibrium, the two-phase speed of sound is considerably smaller than the two single-phase counterparts (less than $30\ m/s$). It follows that the expansion occurs almost entirely in the diverging part. The absolute Mach number at the stator outlet M_3 is 1.6 for Novec649 and 2.1 for MM. The absolute Mach number at the rotor outlet M_6 are 0.6 for Novec649 and 0.9 for MM, hence a classical divergent diffuser is sufficient to recover a portion of the outlet kinetic energy. To avoid excessively lengthy diffusers, a non-negligible fraction of kinetic energy is still lost, which is responsible for around 5 percentage points of efficiency loss $\Delta\eta_{loss}$, as highlighted in Figure 5.

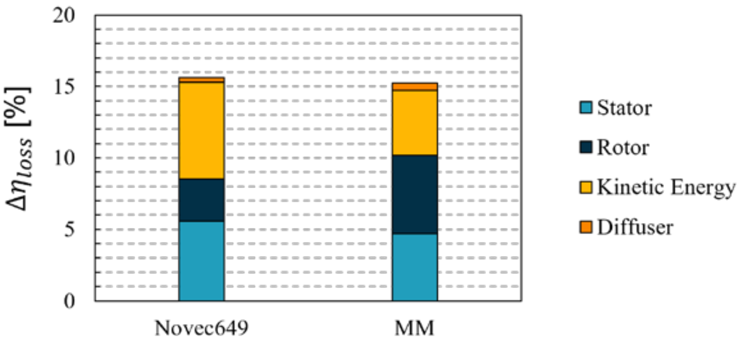

Figure 5: Loss breakdown for radial turbines that maximize cycle efficiency for the two maximum temperature levels (Novec 649 for 423 K and MM for 473 K).

5 CONCLUSIONS

This work has assessed the feasibility of a direct coupling between the organic Rankine cycle, the solar field, and thermal energy storage. The organic fluid remains in the liquid state within the solar field and the thermal energy system, ensuring a relevant technical simplification of these components and reducing the plant footprint. Instead of introducing a throttling valve to deliver dry vapor to the turbine, with a consequent efficiency penalty of the power cycle, a new radial-inflow turbine concept is conceived to handle the two-phase expansion. Leveraging the retrograde shape of the saturation curve of molecularly complex fluids, the whole two-phase expansion is processed within a converging-diverging nozzle, which delivers dry vapor to the subsequent rotor cascade. In this way, blade erosion and additional fluid-dynamic losses associated with the two-phase mixture in the rotating cascade are bypassed. 146

To explore the potential of this system, three maximum temperatures, namely 423K, 473K, and 523K, are considered. It is found that the optimal fluid changes with the cycle maximum temperature. For 423K, the only non-flammable organic fluid that can enable complete liquid vaporization within the stator is Novec649. Multiple fluids exist for the other two temperature levels, including linear (MM, MDM) and cyclic siloxanes (D4, D6).

Efficient turbine designs have been obtained for temperature levels of 423K and 473K, achieving turbine efficiency of ~ 85%. The optimal cycle efficiencies are 11.7% for Novec649 and 17.0% for MM, respectively, with reference to the two maximum temperatures. At $T_{max} = 473$ K, an efficient turbine has been also designed using MDM as the working fluid. However, due to a technical constraint on the minimum cycle pressure (limited to 0.03 bar), the resulting cycle efficiency is 15.7%, i.e., comparably smaller than the MM counterpart. On the contrary, all candidate fluids for the case at 523K (MDM, D4, D6) lead to unfeasible turbine designs, which would have required dealing with supersonic flows in the rotor and the diffuser as well. Therefore, the proposed concept, i.e., direct trilateral ORC with a radial turboexpander, is feasible only if the maximum temperature achieved in the solar field is smaller than 473 K.

Future works will be devoted to developing a model of the overall system; in particular, the effect of the main design parameters will be investigated (i.e., maximum temperature, working fluid) to identify the solution characterized by the best economic attractiveness (i.e., LCOE) taking into account technological constraints. Moreover, the detailed aerodynamic design of the turbo-expander component will be performed to confirm the encouraging, but still preliminary, results coming from the meanline analysis.

NOMENCLATURE

α	absolute flow angle
b	blade height
ε	clearance
η_{cycle}	cycle thermodynamic efficiency
η_{pump}	pump isentropic efficiency
η_{m-e}	mechanical and electrical efficiency
η_{aux}	efficiency for auxiliary consumptions
η_{turb}	turbine isentropic efficiency
M_{w4}	relative Mach number at the rotor inlet
M_6	absolute Mach number at the rotor outlet
L_z	rotor axial length
P_{cond}	condensation pressure
P_{max}	maximum cycle pressure
r	radius
s	specific entropy
T_{cond}	condensation temperature
T_{max}	maximum cycle temperature
$\Delta T_{pp,rec}$	pinch-point temperature in the regenerator
x_1	vapor quality
$\dot{W}_{net}$	electric power

147

REFERENCES

Astolfi (2015), “Techno-economic optimization of low temperature CSP systems based on ORC with screw expanders”, Energy Proc. 69, 1100-1112.

Baines (1998). “A meanline prediction method for radial turbine efficiency”. No. 11, Professional Engineering Publishing for the Institution of Mechanical Engineers, pp. 45–56.

Casati et al. (2013), “Thermal energy storage for solar-powered organic Rankine cycle engines”, Sol. Energy 96, 205-219.

Daily & Nece (1960). “Chamber dimension effects on induced flow and frictional resistance of enclosed rotating disks”. Journal of Fluid Engineering, 82(1), pp. 217–230.

Elliott (1982). “Theory and tests of two-phase turbines”. Tech. rep., Jet Propulsion Laboratory, California Institute of Technology, Pasadena.

Lai & Fischer (2012). “Efficiencies of power flash cycles”. Energy 44, 1017-1027.

Fischer (2011). “Comparison of trilateral cycles and organic Rankine cycles”. Energy 36, 6208-6219.

Glassman (1976). “Computer program for design analysis of radial-inflow turbines”. Tech. rep., NASA Technical Note, TN D-8164, Washington D.C., USA.

Henrik & Per (2013), “Experimental investigation of a Lysholm Turbine operating with superheated, saturated and 2-phase inlet conditions”. App. Therm. Eng. 50(1), 1211-1218.

Kastner & Bhinder (1975). “A method for predicting the performance of a centripetal gas turbine fitted with a nozzle-less volute casing”. In ASME Turbo Expo: Vol. V01BT02A003.

Manfredi et al. (2021). “A reduced-order model for the preliminary design of small-scale radial inflow turbines”. ASME Turbo Expo, paper no. GT2021-59444.

Pelay et al. (2017), “Thermal energy storage systems for concentrated solar power plants”. Renew. Sust. Energy Reviews 79, 82-100.
Perusi & Astolfi (2019), “Comparison between direct and indirect ORCs for CSP applications”, Proceedings of 5th International Seminar on ORC Power Systems, Paper ID: 58.
Read et al (2017). “Optimisation of power generation cycles using saturated liquid expansion to maximise heat recovery”. Proc. Inst. Mech. Eng., Part E: J. Proc. Mech. Eng. 231(1), 57-69.
Rohani et al. (2021). “Optimization of water management plans for CSP plants through simulation of water consumption and cost of treatment based on operational data”. Sol. Energy 223, 278-292.
Skumanich (2011), “CSP at a crossroads: The first solar electric power plants are still proving their worth after three decades, so why aren't we seeing more CSP reach the development stage?”. Renew. Energy Focus 12, 52-55.
Smith (1993). “Development of the trilateral flash cycle system: Part 1: Fundamental considerations”. Proc. Inst. Mech. Eng., Part A: J. Power Energy 207 (3), 179-194.
Smith et al. (1996). “Development of the Trilateral Flash Cycle System: Part 3: The Design of High-Efficiency Two-Phase Screw Expanders”. Proc. Inst. Mech. Eng., Part A: J. Power Energy, 207 (1), 75-93.
Spraker (1987). “Contour clearance losses in radial inflow turbines for turbochargers”. ASME Paper, 871.
White (2021). “Cycle and turbine optimisation for an ORC operating with two-phase expansion”. App. Therm. Eng. 192, 116852.
White (2022). “Investigating the wet-to-dry expansion of organic fluids for power generation”. Int. J. Heat and Mass Transfer 192, 122921.

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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