

David Tomás Sánchez Martínez
Lourdes García Rodríguez
(coordinadores)

Proceedings of the 7th International Seminar on

ORC

Power Systems

Editorial Universidad de Sevilla

Proceedings of the 7th International Seminar on

ORC

Power Systems

David Tomás Sánchez Martínez

Lourdes García Rodríguez

(coordinadores)

Proceedings of the 7th International Seminar on

ORC

Power Systems

(ORC2023)

4th to 6th

SEPTEMBER

SEVILLE 2023

 **EDITORIAL**
UNIVERSIDAD DE SEVILLA

Sevilla, 2024

Comité editorial de
la Editorial Universidad de Sevilla:

Araceli López Serena
(Directora)

Elena Leal Abad
(Subdirectora)

Concepción Barrero Rodríguez
Rafael Fernández Chacón
María Gracia García Martín
María del Pópulo Pablo-Romero Gil-Delgado
Manuel Padilla Cruz
Marta Palenque
María Eugenia Petit-Breuilh Sepúlveda
Marina Ramos Serrano
José-Leonardo Ruiz Sánchez
Antonio Tejedor Cabrera

Review chairs of the 7th International Seminar on ORC Power Systems

Prof. Christoph Wieland (University of Duisburg-Essen) - *Review Chair*

Prof. Sotirios Karellas (National Technical University of Athens) - *Review Co-Chair*

Prof. Teemu Turunen-Saaresti (LUT University) - *Review Co-Chair*

Dr. Diego-César Alarcón-Padilla (Plataforma Solar de Almería - CIEMAT) - *Review Co-Chair*

Dr. Francesco Crespi (Universidad de Sevilla) - *Review Co-Chair*

Esta obra se distribuye con la licencia

Creative Commons Atribución-NoComercial-SinDerivadas 4.0 Internacional ([CC BY-NC-ND 4.0](https://creativecommons.org/licenses/by-nc-nd/4.0/))



Usted es libre de:

Compartir — copiar y redistribuir el material en cualquier medio o formato

La licencianta no puede revocar estas libertades en tanto usted siga los términos de la licencia

Bajo los siguientes términos:

Atribución — Usted debe dar crédito de manera adecuada, brindar un enlace a la licencia, e indicar si se han realizado cambios . Puede hacerlo en cualquier forma razonable, pero no de forma tal que sugiera que usted o su uso tienen el apoyo de la licencianta.

NoComercial — Usted no puede hacer uso del material con propósitos comerciales .

SinDerivadas — Si remezcla, transforma o crea a partir del material, no podrá distribuir el material modificado.

No hay restricciones adicionales — No puede aplicar términos legales ni medidas tecnológicas que restrinjan legalmente a otras a hacer cualquier uso permitido por la licencia.

© Editorial Universidad de Sevilla 2024

c/ Porvenir, 27 - 41013 Sevilla.

Tlfs.: 954 487 447; 954 487 451; Fax: 954 487 443

Correo electrónico: info-eus@us.es

Web: <https://editorial.us.es>

© [David Tomás Sánchez Martínez](#) y [Lourdes García Rodríguez](#)
(coordinadores)

© De los textos, los autores 2024

ISBN 978-84-472-2745-7

DOI: <https://dx.doi.org/10.12795/9788447227457>

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 Schifflachner, 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 Schiffler, 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 Schiffler, 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

Optimization of a Partially Evaporating Organic Rankine Cycle with thermal non-equilibrium expansion.

Xander van Heule^{1,2,*}, Tasos Skiadopoulos³, Dimitris Manolakos³, Michel De Paepe^{1,2}, Steven Lecompte^{1,2}

¹ Ghent University, Department of Electromechanical, systems and Metal Engineering, Sint-Pietersnieuwstraat 41 Ghent, Belgium

² Flanders Make, Leuven, Belgium, FlandersMake@Ugent.be

³ Agricultural University of Athens, Department of Agricultural Engineering, Iera Odos street 75 Athens, Greece

*Corresponding Author: xander.vanheule@ugent.be

ABSTRACT

The Trilateral Flash Cycle (TFC) is an alternative to the Organic Rankine Cycle (ORC). The TFC have been shown to have greater exergy efficiencies compared to the ORC in low-grade heat-to-power conversion. This is a result of the more efficient heat transfer from the heat carrier to the working fluid, even though the TFC has inherently a lower thermal efficiency. However, these results are based on cycle modeling assuming equilibrium conditions, but the actual two-phase expansion process is a non-equilibrium process. Thermal non-equilibrium between vapour and liquid occurs during the evaporation (or flashing) of the working fluid during the two-phase expansion process. The liquid phase has a temperature greater than the corresponding pressure's saturation temperature and the equilibrium assumption overestimates the actual vapour quality. In a previous work, this non-equilibrium expansion was modeled and predicted based on the homogeneous relaxation model (HRM). In this work, the impact of the non-equilibrium process on the efficiency of the TFC is investigated and compared to the equilibrium model. The overall power recuperation is around 86% lower when including the thermal non-equilibrium nature of the expansion process. Therefore, the thermodynamic non-equilibrium losses should thus be incorporated when predicting the performance of a TFC.

176

1 INTRODUCTION

The reduction in greenhouse gas emissions, to reduce the effects of climate change, consists of a wide variety of possible actions. One such action is the reduction of the total process losses through recuperative methods. One of the most significant losses with the current global infrastructure is waste heat (Firth *et al.*, 2019, Forman *et al.*, 2016) for which there exist multiple methods to recover this lost energy. The estimated global waste heat is around 52% of the global energy input of which around 65% is low-temperature waste heat. If these waste energy streams could be efficiently harvested, it would reduce the required initial energy input as a larger share of this energy would become useful, reducing greenhouse gas emissions in the process. The largest untapped sector of waste heat was the transport sector according to Firth *et al.* (2019). Methodologies to harvest waste heat exist such as the Organic Rankine Cycle (ORC) or variants thereof. One such variant is the Trilateral Flash cycle (TFC) which does not evaporate the working fluid in the evaporator. Instead, a saturated liquid is expanded to the low pressure compared to a superheated vapour in the basic ORC. This cycle has larger net power output compared to the basic ORC (Li *et al.*, 2017, Fischer, 2011), especially with lower heat source temperatures (Woodland *et al.*, 2020). This is a result of the better temperature profile matching between the waste heat carrier and the working fluid (Lecompte *et al.*, 2015a) within the evaporator. However, these studies do assume similar isentropic efficiencies for both vapour and two-phase expanders. It is also possible to partially evaporate the working fluid within the evaporator of the cycle, this cycle is

known as the Partially Evaporating Organic Rankine Cycle (PEORC). This reduces the temperature profile matching but also decreases the volume flow rate of the cycle compared to the TFC, which can become large (Fischer, 2011). This can result in higher net power output of the cycle (Lecompte *et al.*, 2013) due to the reduction in required pumping power. This is especially the case when the pump's isentropic efficiency is low.

In literature, when cycles are studied which incorporate two-phase expansion, assumptions are made to describe this process. As mentioned, it is often based upon an isentropic efficiency, as similarly done for vapour expansion processes. Another assumption often made is the thermodynamic stability of the process. However, it has been shown that this assumption does, depending on the expander type, not have good agreement with experimental data. Currently, this assumption corresponds to experimental data for Lysholm expanders operating in two-phase conditions (Öhman and Lundqvist, 2013) but not for reciprocating expanders (Kanno and Shikazono, 2015) where the non-equilibrium effects are not negligible and represent a substantial part of the losses.

In previous work (van Heule *et al.*, 2023), the two-phase expansion within a reciprocating expander was modelled by using an adapted homogeneous relaxation model (HRM) and compared to the homogeneous equilibrium model (HEM). The HEM is based on the conservation equations with the assumption that the mixture is in thermodynamic equilibrium at all times. This implies that evaporation can happen instantaneously. The HRM is based on the HEM but without the thermal equilibrium assumption. Instead, a vapour generation rate equation is used which describes the evaporation rate based on a relaxation equation (Downar-Zapolski *et al.*, 1996). Hereby it is possible to have a mixture of saturated vapour and superheated liquid at the same chamber pressure as was also experimentally observed by Kanno and Shikazono (2015). In this work, this model is implemented within a Trilateral Flash cycle and optimized based on the cycle's net power output which is compared to an optimization with the HEM expansion.

2 METHODS

177

2.1 Modeling of thermal non-equilibrium expansion

The thermal non-equilibrium occurring within the expander chamber of a reciprocating expander was chosen to be modelled with an adapted Homogeneous Relaxation Model. This model assumes that the phases have the same pressure, as they occupy the same expansion volume, but not that the phases necessarily have the same temperature even though the expansion occurs within the two-phase region. This is a result of an evaporation equation that limits the evaporation rate through an empirical thermal relaxation time as expressed in equations (1) and (2):

$$\frac{\Gamma_g}{\rho} = -\frac{x - \bar{x}}{\Theta} \quad (1)$$

$$\Theta = \Theta_0 \cdot \epsilon^a \cdot \psi^b \quad (2)$$

, where Γ_g is the volumetric vapour generation rate, ρ the mixture density, x the actual vapour quality, $\bar{x}$ the equilibrium vapour quality, Θ the relaxation time, ϵ the void fraction and ψ the non-dimensional pressure difference defined in equations (3) and (4) depending on the operational pressure.

$$\psi = \frac{p_s - p}{p_s} \quad \text{if } p < p_{\text{lim}} \quad (3)$$

$$\psi = \frac{p_s - p}{p_c - p_s} \quad \text{if } p > p_{\text{lim}} \quad (4)$$

where p_s is the saturation pressure corresponding to the liquid superheat, p is the actual pressure, p_c is the critical pressure, and p_{lim} an empirical pressure threshold. The values of the numerical parameters Θ_0 , a , and b in equation (2), determined experimentally by Downar-Zapolski *et al.* (1996), are respectively $6.51 \cdot 10^{-4} \text{ s}$, -0.257 and -2.24 when equation (3) is used and $3.84 \cdot 10^{-7} \text{ s}$, -0.54 and $-$

1.76 when equation (4) is used and the empirical pressure threshold was 10 bar. These values were based on water flowing through a diverging nozzle. This was adapted by van Heule *et al.* (2023) based on the experimental data of Kanno and Shikazono (2017) who performed expansion experiments with water in a piston moving with a trapezoidal movement profile. Based on this experimental data, the best fitting values of the numerical parameters Θ_0 , a , and b are $9 \times 10^{-15} \text{ s}$, -0.7 , and -15.7 respectively but only for the definition using equation (3) as only pressures beneath 10 bar were experimented on.

The model keeps track of the mass and internal energy of each phase separately throughout the expansion process. The actual vapour quality can easily be calculated in each time step based on the masses of each phase as expressed in equation (5), while the equilibrium vapour fraction is a function of the total internal energy of the mixture within the expansion chamber and the saturated specific internal energy values corresponding with the chamber pressure as expressed in equation (6):

$$x = \frac{m_g}{m_l + m_g} \quad (5)$$

$$\bar{x} = \frac{u - u_l}{u_g - u_l} \quad (6)$$

where m_g is the vapour mass, m_l the liquid mass, u_g and u_l the specific internal energy of saturated vapour and liquid at the working chamber respectively, and u the specific internal energy of the entire mixture. All fluid properties are obtained through the REFPROP 10 (Lemmon *et al.*, 2018) library including the metastable liquid temperature, required for p_s in equations (3) and (4), based on the specific internal energy of the liquid phase and the working chamber pressure. The working chamber pressure in turn is obtained through the saturated vapour phase assumption of the HRM model through REFPROP.

2.2 Partial evaporating organic Rankine cycle

As mentioned in Section 1, the Partial Evaporating ORC (PEORC) is similar to a basic ORC but the working fluid is not fully evaporated within the evaporator. The PEORC used in this study is for a constant heat carrier flow, reciprocating expander geometry, condensing pressure, and evaporating pressure. The boundary conditions used are listed in Table 1 and Figure 1 is an example of the cycle with a vapour quality of 0.3. Point 1 on this figure is determined by the pump subcooling and the condensing pressure. Point 2 is calculated based on constant isentropic pump efficiency. Point 3, the inlet of the expander, is determined by the evaporating pressure and the initial vapour quality of the expansion. Point 4* is the state at the end of the expansion stroke and model. However, this point is not yet in equilibrium and does therefore not have a defined location within this type of temperature-entropy diagram. Here it is plotted on the location with the same density and specific internal energy. The process from point 4* to 4 on Figure 1 is an isochoric process between the metastable point 4* and thermodynamic stable point 4 at the low pressure. This thus includes both non-equilibrium losses and over- or under-expansion losses. Lastly, an isobaric heat rejection process occurs within the condensor to the predefined subcooling to close the cycle. The pinch point condition within the evaporator can occur either at the heat source exit or within the evaporator where the working fluid starts boiling. Which condition occurs depends on the vapour quality at which expansion is occurring. For low vapour qualities at the expander inlet, the pinch point will occur at the heat source outlet, while it occurs at the working fluid saturated point for higher expander vapour qualities. The cycle can dynamically switch between the two conditions depending on which assumed location indeed gives a higher temperature difference at the other location. The geometric properties of the free piston expander are also listed in Table 1 and are based on a reciprocating expander for waste heat recovery of a truck engine (Rijpkema *et al.*, 2021). The stroke and expander cycle speed can be altered based on the requirements of the mass flow rate coupled with the choice of expansion inlet quality. The intake stroke is taken as 25% of the entire expanding stroke (Glavatskaya *et al.*, 2012).

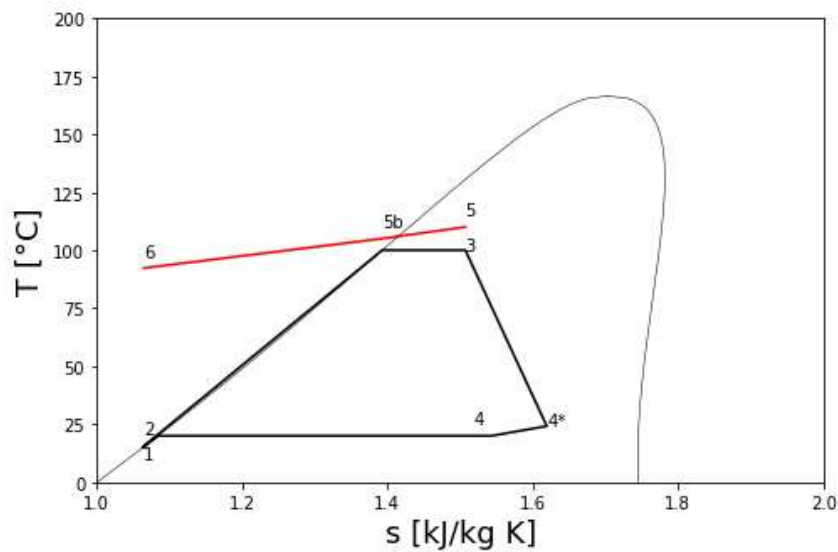


Figure 1: TS diagram of PEORC with expander inlet vapour quality equal to 0.3 where point 4* represents a metastable condition with corresponding density and specific internal energy.

Table 1: Boundary conditions of the partially evaporating Organic Rankine Cycle.

Condensing temperature	20 °C
Evaporating temperature	100 °C
Working fluid	R1233ZD(E)
Heat carrier	Air
Heat source temperature	110 °C
Heat source flow rate	0.2 kg/s
Subcooling pump	5 °C
Evaporator pinch point	5 °C
Isentropic pump efficiency	0.7
Vapour quality at expander inlet	0-1
Expander diameter	0.09 m
Expander clearance length	0.003 m
Intake stroke duration	25 %

In the following, the cycles will be compared based upon the net power output as defined in equations (7) to (9):

$$W_{net} = W_{exp} - W_{pump} \quad (7)$$

$$W_{pump} = \dot{m}_{wf} \cdot (h_2 - h_1) \quad (8)$$

$$W_{exp} = \frac{\int p \cdot dV}{t_{cycle}} \quad (9)$$

where W_{net} is the net power output of the cycle, W_{exp} the power delivered by the expander during the expansion stroke, W_{pump} the power required to run the pump, $\dot{m}_{wf}$ the mass flow rate of the working fluid, h_2 and h_1 the specific enthalpy at the outlet and inlet of the pump respectively, p the pressure within the working chamber, V the volume of the working chamber, and t_{cycle} the duration of one expander stroke cycle. Because the heat source is taken constant, this power is also a measure of the second law efficiency as defined in equation (10) (Lecompte *et al.*, 2015b):

$$\eta_{II} = \frac{W_{net}}{E_{hs,in}} \quad (10)$$

where η_{II} is the second law efficiency and $E_{hs,in}$ is the exergy flow within the system of the heat source. The isentropic efficiency of the expander is defined in equation (11) where h_3 is the specific enthalpy at the expander inlet (point 3 in Figure 1) and h_{4s}^* the isentropic specific enthalpy of point h_4^* in Figure 1.

$$\eta_s = \frac{W_{exp}}{m_{wf} \cdot (h_3 - h_{4s}^*)} \quad (11)$$

3 RESULTS

3.1 Impact of vapour quality on working fluid flowrate

The choice of vapour quality at the start of expansion has a large impact on the required flow rate of the working fluid as presented in Figure 2.

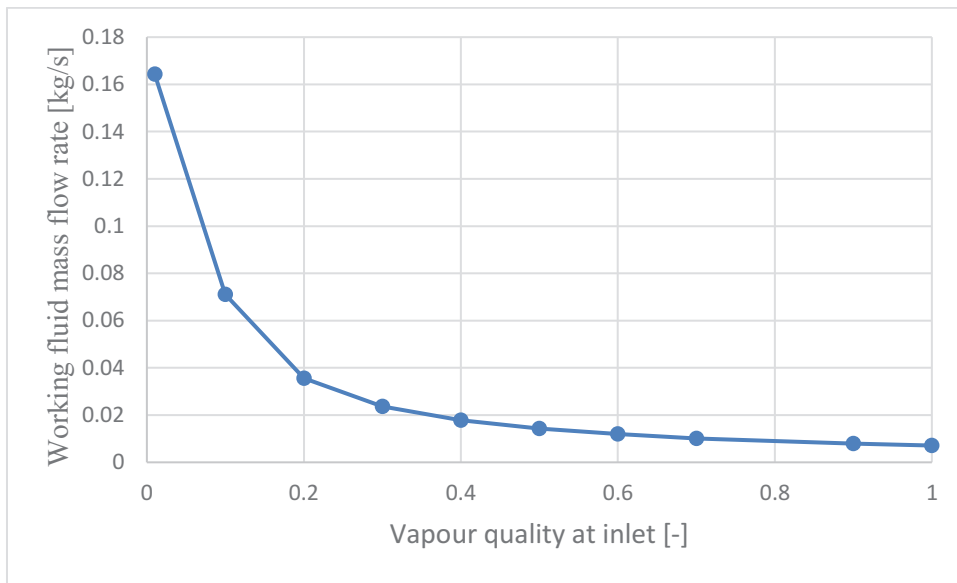


Figure 2: Required working fluid mass flow rate in function of vapour quality.

As mentioned, this phenomenon of large flow rates is a known issue with the TFC as the required pumping power drastically increases. Choosing a vapour quality already slightly higher than saturated liquid already drastically reduces the required pumping power and thus increases the net power output of the cycle. The difference in the required mass flow rate is also problematic for the chosen expander as the dimensions were predefined. One possibility would be to use multiple expanders and assume the two phase inlet condition is equally split across the different expanders. As an example, using two of these expanders for an inlet vapour quality of 0.1 increases the net power output compared to only one expander as each expander only has half the required mass flow rate resulting in less under expansion losses. However, this does not result in a higher overall net power production compared to other vapour qualities operating with one expander. Thus in the following discussion, only one expander is used irrespective of the vapour quality to find the optimal operation point.

3.2 Cycle optimization

First, the cycle from Table 1 will be optimized for the net power production, defined in Equation (7), with respect to the vapour quality at the end of the evaporator, point 3 in Figure 1. For this configuration, the optimal vapour quality is found to be 0.51 with a net power production of 477.9 W. The net power production in function of vapour quality is shown in Figure 3 where the expanders strokes per minute are optimized on each operation point. A lower vapour quality of the optimum is not beneficial to the cycle as the increase in pumping power is dominant, while an increase in vapour quality is not beneficial

due to a reduced heat transfer within the evaporator as a result from the pinch point condition, resulting in less net power production. The optimum point found matches with the speed where the expander on which the dimensions are based (Rijpkema *et al.*, 2021) has an isentropic filling factor of 1. This indicates the important impact of the expander design choice on the optimum working point of the cycle. The isentropic efficiency of the expansion (equation (11)) is also included in Figure 3. This is rather constant around the optimum design point. The impact of the dimensions of the expander on the required strokes per minute and net power is presented in Table 2. A change in the clearance length of the dead volume or the diameter has an impact on the net power but a respectively big change in optimal strokes per minute. The optimum with these other expander dimensions changes for the same cycle.

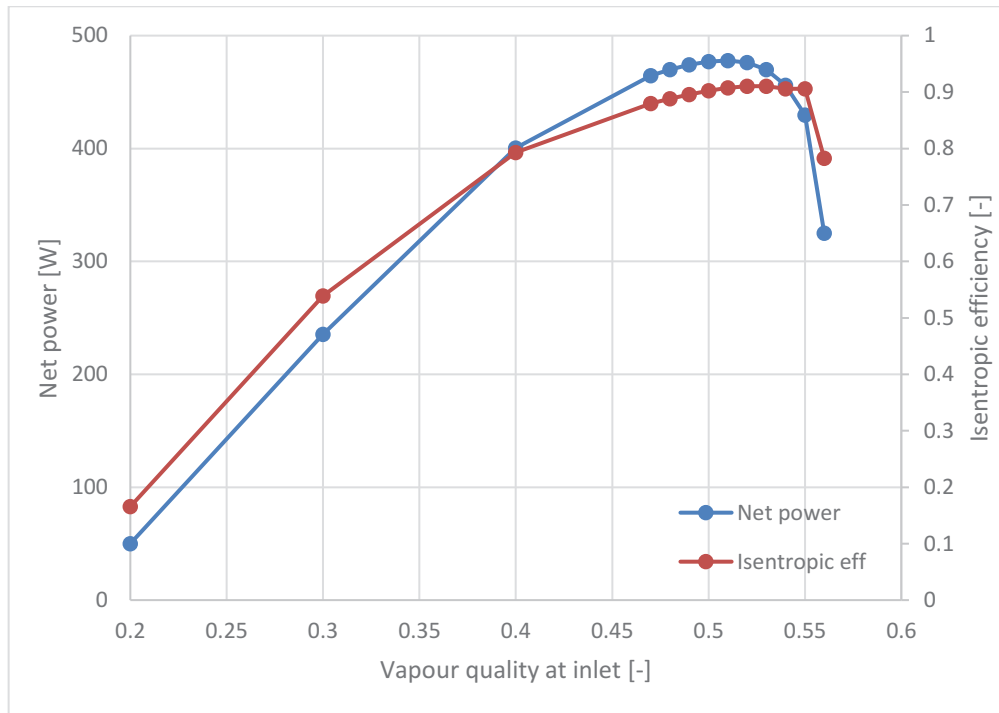


Figure 3: Net power produced of the described TFC in function of vapour quality.

Table 2: Impact of expander dimensions on cycle performance with an expander inlet vapour quality of 0.5.

Diameter [m]	Clearance length [m]	Required strokes per minute [rpm]	Net power [W]
0.09	0.003	963	477.0
0.09	0.002	1575	463.4
0.09	0.004	667	468.0
0.08	0.003	1394	429.9
0.10	0.003	634	459.1

4 DISCUSSION

The performance of the PEORC around the found optimum is compared to the same cycle, but the expansion is modeled without the HRM. It is thus assumed that equilibrium is achieved throughout the entire process at each point in time. The results are shown in Table 3. Firstly the net power with the incorporation of the homogeneous relaxation model is consistently around 86% of the net power output without the HRM which is a non-negligible amount that should be taken into account in cycle comparisons. However, this is less than the benefit gained when comparing the PEORC to a Basic ORC.

It is hereby speculated that the PEORC is still beneficial compared to the Basic ORC for low-temperature heat sources, but in a lesser extent than originally derived. The optimum for the cycle, without incorporating the non-equilibrium expansion, occurs at a slightly lower vapour quality compared to the cycle including the HRM.

Table 3: Cycle performance with HRM and HEM expansion using the same cycle time.

Vapour quality [-]	Net power HRM [W]	Net power HEM [W]
0.54	456.0	526.1
0.53	470.0	543.3
0.52	476.1	551.8
0.51	477.9	555.1
0.50	477.0	555.5
0.49	474.2	553.7
0.48	470.0	550.5

5 CONCLUSIONS

A Trilateral Flash Cycle (TFC) is modeled for a constant heat source, expander design, high pressure, and low pressure. The expansion within the TFC incorporates the thermal non-equilibrium phenomena occurring within a reciprocating expander. This is incorporated through the use of the Homogeneous Relaxation Model (HRM) where the liquid phase can be in a metastable superheated state as the evaporation occurs slower than thermodynamic stable conditions would require. The mass flow rate of the working fluid is heavily dependent on the vapour quality at the evaporator outlet, resulting in very high pumping power for low vapour qualities and thus a low net power output. On the other hand, a decrease in transferred heat within the evaporator for increasing vapour qualities also results in lower net power outputs. Thus an optimum occurs for the chosen cycle and expander. With the choices taken in this paper, the optimum was found at a vapour quality of 0.51. The performance of the chosen cycle is only around 86% of the same cycle when the non-equilibrium expansion is not incorporated within the expander model, indicating the importance of this phenomenon within the reciprocating expander.

In future work, the findings will be validated based on an experimental campaign on a two-phase reciprocating piston expander, which is currently under construction. Additionally, the cycle simulation could be adapted to optimize the cycle without predefining the expander dimensions. In this way, an expander can be designed to best fit a certain application.

NOMENCLATURE

ϵ	void fraction	(–)	ρ	density	(kg/m ³)
Θ	relaxation time	(s)	h	specific enthalpy	(J/kg)
m	mass	(kg)	p	pressure	(Pa)
t	time	(s)	V	volume	(m ³)
u	specific internal energy	(J/kg)	W	power	(W)
$\bar{x}$	equilibrium vapour quality	(–)	x	vapour quality	(–)
Γ	volumetric vapour generation rate	(kg/m ³ s)			

Subscript

c	critical
g	vapour phase
l	liquid phase
s	saturated
wf	working fluid

REFERENCES

- Downar-Zapolski, P., Bilicki, Z., Bolle, L., Franco, J., 1996, The non-equilibrium relaxation model for one-dimensional flashing liquid flow, *Int. J. Multiph. Flow*, vol. 22, no. 3: p. 473-483.
- Firth, A., Zhang, B., Yang, A., 2019, Quantification of global waste heat and its environmental effects, *Appl. Energy*, vol. 235, no. 1: p. 1314-1334.
- Fischer, J., 2011, Comparison of trilateral cycles and organic Rankine cycles, *Energy*, vol. 36, no. 1: p. 6208-6219.
- Forman, C., Muritala, I.K., Pardemann, R., Meyer, B., 2016, Estimating the global waste heat potential, *Renewable Sustainable Energy Rev.*, vol. 57, no. 1: p. 1568-1579.
- Glavatskaya, Y., Podevin, P., Lemort, V., Shonda, O., Descombes, G., 2012, Reciprocating expander for an exhaust heat recovery rankine cycle for a passenger car application, *energies*, vol. 5: p. 1751-1765.
- Kanno, H., Shikazono, N., 2015, Experimental and modeling study on adiabatic two-phase expansion in a cylinder, *Int. J. Heat Mass Transf.*, vol. 86, no. 1: p. 755-763.
- Lecompte, S., van den Broek, M., De Paepe, M., 2013, Thermodynamic analysis of the partially evaporating trilateral cycle, *Int. Seminar on ORC power systems*, p. 1-4.
- Lecompte, S., Huisseune, H., van den Broek, M., Vanslambrouck, B., De Paepe, M., 2015a, Review of organic Rankine cycle (ORC) architectures for waste heat recovery, *Renewable Sustainable Energy Rev.*, vol. 47, no. 1: p. 448-461.
- Lecompte, S., Huisseune, H., van den Broek, M., De Paepe, M., 2015b, Methodical thermodynamic analysis and regression models of organic rankine cycle architectures for waste heat recovery, *Energy*, vol. 87, no. 1: p. 60-76.
- Lemmon, E.W., Bell, I.H., Huber, M.L., McLinden, M.O., 2018, NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties-REFPROP, Version 10.0, *National Institute of Standards and Technology*, Standard Reference Data Program, Gaithersburg.
- Li, Z., Lu, Y., Huang, Y., Qian, G., Chen, F., Yu, X., Roskilly, A., 2017, Comparison study of Trilateral Rankine Cycle, Organic Flash Cycle and basic Organic Rankine Cycle for low grade heat recovery, *Energy Procedia*, vol. 142, no. 1: p. 1441-1447.
- Öhman, H., Lundqvist, P., 2013, Experimental investigation of a lysholm turbine operating with superheated, saturated and 2-phase inlet conditions, *Appl. Therm. Eng.*, vol. 50, no. 1: p. 1211-1218.
- Rijpkema, J., Thantla, S., Fridh, J., Andersson, S.B., Munch, K., 2021, Experimental investigation and modeling of a reciprocating piston expander for waste heat recovery from a truck engine, *Appl. Therm. Eng.*, vol. 186, no. 1: p. 1-15.
- van Heule, X., Skiadopoulos, A., Manolakos, D., De Paepe, M., Lecompte, S., 2023, Modelling of two-phase expansion in a reciprocating expander, *Appl. Therm. Eng.*, vol. 218, no. 1: p. 1-10.
- Woodland, B.J., Ziviani, D., Braun, J.E., Groll, E.A., 2020, Considerations on alternative organic Rankine Cycle configurations for low-grade waste heat recovery, *Energy*, vol. 193, no. 1: p. 1-17.

ACKNOWLEDGEMENT

I would like to thank the Research Foundation-Flanders for their financial support through FWO-Flanders grants (1SD9723N).

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.