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Lourdes García Rodríguez
(coordinadores)

Proceedings of the 7th International Seminar on ORC Power Systems

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STUDYING CARBON DIOXIDE AND ACETONE MIXTURES IN A SINGLE-STAGE ABSORPTION-COMPRESSION CYCLE FOR HEATING AND COOLING APPLICATIONS

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ABSTRACT

This communication analyzes the performance of a zeotropic fluid, composed by the mixture of carbon dioxide and acetone, in a vapor compression cycle with a solution circuit. The working fluid is characterized by a high temperature glide that depends on the mixture composition. The high critical temperature of the acetone and the good thermal properties of carbon dioxide makes this mixture a promising heat transfer fluid for industrial heat pumps that need to supply energy for heating and cooling processes. The heat pump analyzed has these components: evaporator, compressor, condenser, two internal heat exchangers and an expansion valve. In addition, a second liquid line with a solution pump is used to circulate the liquid from the gas-liquid separator to an internal heat exchanger, and then, to the condenser. In this way, the gas-liquid separator allows the fluid to leave the evaporator as a vapor-liquid mixture. This heat pump configuration working with the CO_2/acetone mixture could provide the energy needs of an industry that requires both heating and cooling. Depending on the binary mixture composition, the source and sink temperatures change as well as the coefficient of performance. For instance, an 55% CO_2/45% acetone in mass fraction, can provide heat to the sink at an average thermodynamic temperature of 110ºC, and refrigeration at an average thermodynamic temperature of 0ºC, showing a total COP of 2.55. This configuration would work at a high pressure of 40 bar and a low pressure of 10 bar.

1 INTRODUCTION

Decarbonizing process heating and process cooling in industry is key to meet the EU climate goals. Indeed, The EU's heating and cooling needs in 2020 accounted for half of its total gross final energy consumption (Eurostat, 2022). Heating in industrial processes accounted for approximately 25% of global energy consumption in 2021 (Thiel, 2021). In this sense, fossil fuels provided most of this heat. Only 13% of process heat in the EU is provided by renewable sources, 11% of this being provided by biomass, while electricity provides 12% of the EU' s process heat – some of this may be renewable, depending on the local power generation mix (Elsand et al., 2017).

However, the decarbonization of industry is a difficult task because of the inhomogeneous array of processes and temperature requirements (Arpagaus et al., 2018). For instance, steel and cement production may require temperature far beyond 1000°C, while some food industry processes may need only 40-80°C for processes like homogenization or pasteurization. Heat pump technology is emerging as a flexible approach to decarbonizing heating and cooling for medium temperatures. Regarding the heating applications, there are industrial heat pumps available that can provide industrial process heat at temperatures up to 150ºC with high coefficient of performance (Olsson and Schipfer, 2021).

Regarding the simultaneous heating and cooling, an ammonia-based compression heat pump is studied by (Ayou et al., 2022) to provide simultaneous heating at 72ºC and cooling at 4ºC for milk pasteurization.

There is a great interest in exploring new heat pump refrigerants with low Global Warming Potential that can help in the decarbonization of industry with low environmental impact. The binary mixture of carbon dioxide and acetone has been proposed as a good candidate for such a task. Previous studies have experimentally characterized the zeotropic phase change of this refrigerant, which shows high temperature glides that depend on the mixture composition (Höhler et al., 2018) (Ramírez-Ramos et al., 2021). In the same way, a recent paper of the authors explored the use of this mixture for high temperature heat pumps in the range of 150 - 220ºC (Gómez-Hernández et al., 2023).

A zeotropic refrigerant with high temperature glide may present some drawbacks. For instance, when comparing a pure fluid with a zeotropic refrigerant, the phase change process includes a new thermal resistance that reduces the heat transfer coefficient (Huang et al., 2022). In the same way, the compressor may reduce its efficiency due to the inhomogeneous behavior of the mixture during the compression process (Roskosch et al., 2021). However, the potential application of this low GWP refrigerant is mandatory before addressing the aforementioned challenges.

This communication analyzes a single-stage compression-absorption cycle using a binary mixture of carbon dioxide and acetone as refrigerant. This heat pump layout uses a gas-liquid separator to reduce the power consumption of the compressor by changing the refrigerant composition. To the best author knowledge, this study is the first attempt to study the binary mixture of carbon dioxide and acetone to supply simultaneously both heating and refrigeration at milk pasteurization temperatures. Partial phase change processes are considered in both evaporator and condenser in order to supply heat at heating temperatures above 80ºC and cooling at temperatures below 0ºC. The results show the influence of the operating conditions of the gas-liquid separator on the heat sink temperature and on the coefficient of performance for different refrigerant compositions. **459**

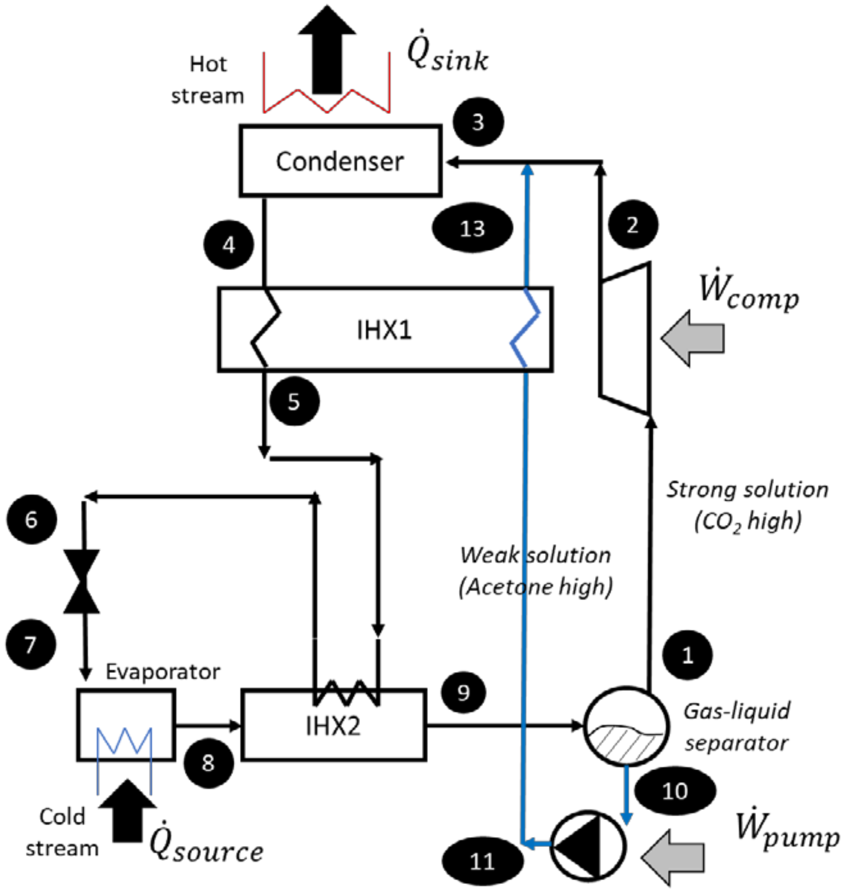
2 METHODS

This section describes the heat pump layout, the main thermodynamic properties of the refrigerant and the main assumptions used to calculate the performance indicators.

2.1 Heat pump layout

Figure 1 shows the proposed heat pump layout considered in this study. This single-stage absorption-compression cycle is composed by a gas-liquid separator, a compressor, a pump, two internal heat exchangers, the condenser and the evaporator. The key element is the gas-liquid separator, which is assumed to be at equilibrium for the desired pressure and temperature. The gas-liquid separator divides the flow into a vapor, which flows into the compressor, and a liquid, that is pumped up to the compressor pressure discharge. The vapor has a high content of the most volatile component, CO_2 in this study, while the liquid has a high content of acetone. The liquid is preheated in an internal heat exchanger (IHX1). Then, the compressed vapor stream and the preheated liquid is adiabatically mixed, flowing into the condenser at state 3.

Heat is transferred to the sink during the partial phase-change process that is produced in the condenser. The outlet condenser temperature (state 4) is an input data. The condensation process is completely achieved transferring heat to the acetone high liquid in IHX1, and preheating the refrigerant in the second internal heat exchanger (IHX2). Finally, the refrigerant is at saturated liquid conditions, and then, expanded in the isenthalpic valve up to the evaporator pressure. Such pressure determines the heat received from the source at low temperature. The cycle is closed with the IHX2, that heats up the refrigerant up to the inlet conditions at the gas-liquid separator.



460

Figure 1: Single-stage absorption-compression cycle.

2.2 Refrigerant properties

The binary mixture of carbon dioxide and acetone shows a zeotropic behavior during phase change. Table 1 shows the properties of both pure fluids. Temperature glides up to 120 K can be obtained depending on the mixture composition and the operating pressure (Gómez-Hernández et al., 2023). This work analyzes the performance of the single-stage absorption-compression cycle for an evaporator pressure of 10 bar and for a condenser pressure of 40 bar. Therefore, the temperature evolution as a function of the mixture quality for both pressures is presented in Figures 2 and 3.

Table 1: Pure fluid properties.

Refrigerant	T_{crit} [ºC]	P_{crit} [bar]	NBP [ºC]	GWP100 [-]	ODP [-]
Acetone	234.95	46.92	56.07	0.5	0
Carbon dioxide	30.98	73.77	-78.46[a]	1	0

[a] Normal Sublimation Point

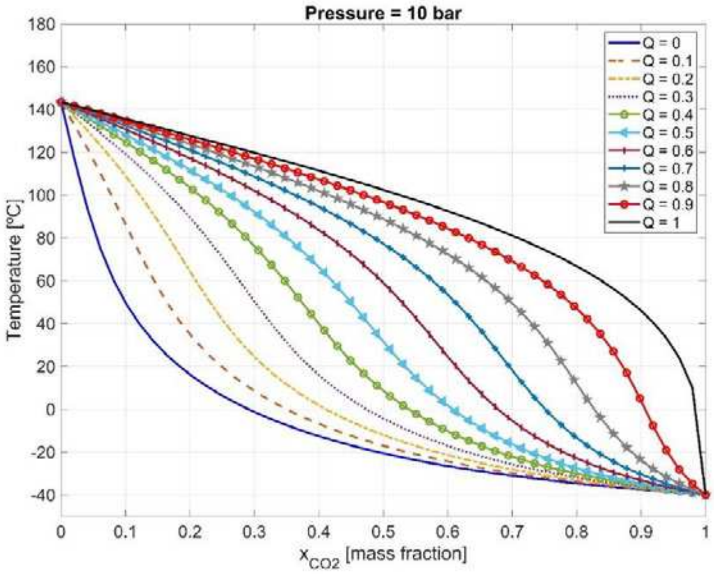


Figure 2: Temperature evolution as a function of the CO_2 content and the mixture quality for a pressure of 10 bar.

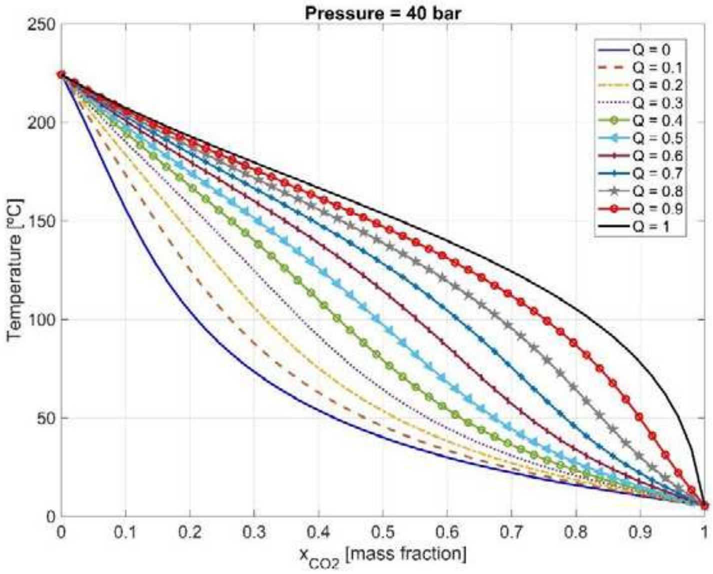


Figure 3: Temperature evolution as a function of the CO_2 content and the mixture quality for a pressure of 40 bar.

Both figures show that the mixture temperature decreases as the CO_2 content increases due to the low critical temperature of this fluid. Figure 2 shows the temperature profiles for the evaporator pressure (10 bar). The low temperatures achieved for binary mixtures with a CO_2 content ranging from 0.3 to 0.9 makes the study of refrigeration applications interesting. Figure 3 shows the temperature profiles when working at 40 bar in the condenser. In this case, the saturated vapor temperatures may help choosing the temperature of the heat sink, and thus, the CO_2 content in the refrigerant.

2.3 Thermodynamic analysis

The heat pump cycle studied in this communication is modeled following these assumptions:

- Steady state conditions.
- All components are adiabatic.

- Isobaric heat exchangers.
- Isentropic compressor efficiency of 70%.
- Isentropic pump efficiency of 80%.
- Internal heat exchanger efficiency of 80%.
- Isenthalpic valve expansion.
- Refprop software (Lemmon et al., 2018) is employed to obtain the thermodynamic properties of the CO_2/acetone mixture.
- Gas liquid separation process modeled following the Vapor-Liquid Equilibrium results experimentally obtained in (Ramírez-Ramos et al., 2021). This allows the calculation of the mass flow rates and the refrigerant composition for both vapor and liquid, which have, respectively, high and low CO_2 content.

The input parameters to the model are:

- High and low pressures (P_{cond} and P_{ev}).
- Gas-liquid separator temperature ($T_9 = T_{10} = T_{11}$).
- Refrigerant composition at the inlet of the gas-liquid separator, $(x_{CO2})_9$ and $(x_{acetone})_9$.
- Outlet condenser temperature (T_4), which is calculated as $T_4 = T_9 + 15$. This condition also sets the refrigerant quality (Q_4) due to the zeotropic behavior of the refrigerant.
- Saturated liquid conditions at the valve inlet ($Q_6 = 0$).

Therefore, the evaporation and condensation operating conditions change as a function of the refrigerant composition. In order to consider also the high temperature glide of the refrigerant, the average thermodynamic temperature is used to calculate the average sink and source temperatures, equation 1:

$$\bar{T} = \frac{\Delta h}{\Delta s} \tag{1}$$

462

The coefficient of performance (COP) is calculated for both hot and cold applications as:

$$COP = \frac{\dot{Q}}{\dot{W}_{comp} + \dot{W}_{pump}} \tag{2}$$

Being the total COP of the heat pump:

$$COP_{total} = \frac{\dot{Q}_{sink} + \dot{Q}_{source}}{\dot{W}_{comp} + \dot{W}_{pump}} \tag{3}$$

3 RESULTS

This section first describes the evolution of the outlet valve temperature (T_7) as a function of the refrigerant composition. Then, the main outcomes of the single-stage absorption-compression cycle are presented.

Figure 4 shows the decrease in temperature at the outlet valve as the CO_2 content increases in the binary mixture. CO_2 mass fractions above 45% may be interesting for refrigeration applications. Very low temperatures are obtained for CO_2 contents above 60%.

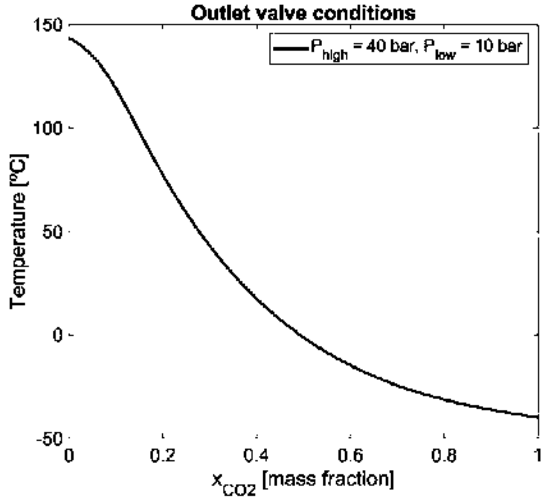


Figure 4. Outlet temperature of the isenthalpic valve for a pressure difference of 40 to 10 bar.

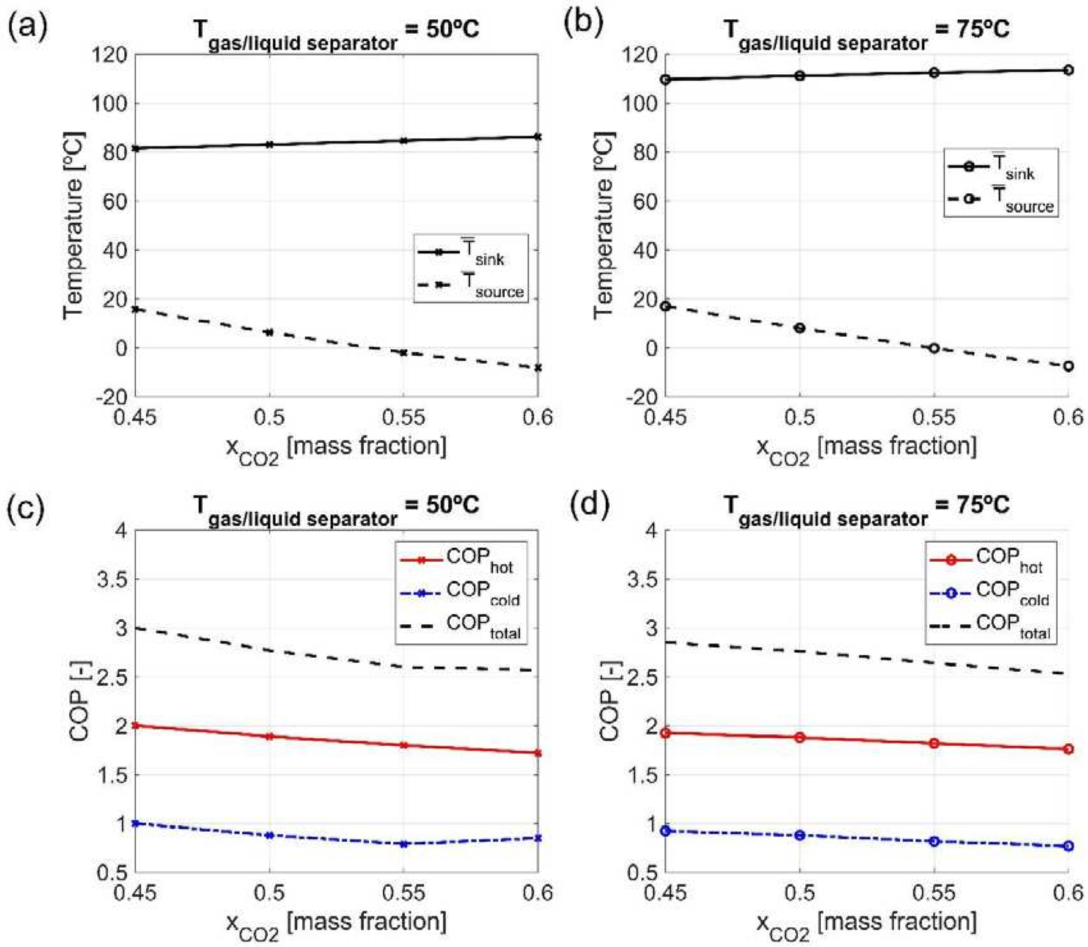


Figure 5. Main performance indicators as a function of the refrigerant composition: (a) average thermodynamic temperatures and (c) COP for a gas-liquid separator at 50ºC, (b) average thermodynamic temperatures and (d) COP for a gas-liquid separator at 75ºC.

Figure 5 explores the average thermodynamic temperature and the COP for CO_2 contents of 45-60% for two temperatures in the gas-liquid separator. In the case of T_9 = 50ºC, the thermodynamic average temperature of the heat sink is around 80ºC (Fig. 5-a), while the heat source presents a wider temperature range. CO_2 mass fractions above 55% achieve average temperatures below 0ºC. COP values decrease with the increase of CO_2 due to the higher temperature difference between the sink and the source (Fig. 5-c). In the case of T_9 = 75ºC, the heat sink temperature increases about 30ºC (Fig. 5-b), while the heat source temperature remains constant compared to the previous case. The higher gas-liquid separator temperature increases the acetone content in the vapor that flows into the compressor, and thus, modifies the thermal properties of the refrigerant during the compression. However, the COP remains constant (Fig. 5-d).

4 CONCLUSIONS

This communication explores the use of mixtures of carbon dioxide and acetone as refrigerant of a single-stage absorption-compression cycle for both cooling and heating applications. The conclusions can be summarized as follows:

- The mixture presents a high temperature glide, which likely disadvantageous effect on the heat transfer process during phase change has been neglected in this study.
- Binary mixtures of 45 – 60% in mass fractions of CO_2 could supply the heating and cooling demands of many industrial processes. The target temperatures are above 80ºC for the heat sink, and below 0ºC for the heat source.
- A COP of 2.55 is obtained for a mass fraction of 55% CO_2 for an average thermodynamic temperature of 110ºC in the condenser, and an average thermodynamic temperature of 0ºC in the evaporator when the gas-liquid separator temperature is 75ºC.
- The operating conditions of the gas-liquid separator significantly influence the heat sink temperature, while keeping fairly constant the heat source temperatures and the COP.

NOMENCLATURE

COP	coefficient of performance (-)
GWP	global warming potential (-)
IHX	internal heat exchanger
NBP	normal boiling point (ºC)
ODP	ozone depletion potential (-)
P	pressure (bar)
Q	quality (-)
T	temperature (ºC)
$\bar{T}$	average thermodynamic temperature (ºC)
x	mass fraction (-)

Subscript

cond	condenser
crit	critical
ev	evaporator

REFERENCES

Arpagaus C, Bless F, Uhlmann M, Schiffmann J, Bertsch SS, 2018. High temperature heat pumps: market overview, state of the art, research status, refrigerants, and application potentials. Energy; 152:985 – 1010.

Ayou DS, Hargiyanto R, Coronas A, 2022. Ammonia-based compression heat pumps for simultaneous heating and cooling applications in milk pasteurization processes: Performance evaluation, Applied Thermal Engineering, Volume 217, 119168.

Elsand R, Fleiter T, Jakob M, Reiter U, Harmsen R, Mines P, Rivière P, Dittmann F, 2017. Heat Roadmap Europe. Heating and cooling: facts and figures, the transformation towards a low-carbon heating and cooling sector.

Eurostat, 2022. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions 'REPowerEU plan' (COM (2022) 230 final).

Gómez-Hernández J, Grimes R, Briongos JV, Marugán-Cruz C, Santana D, 2023. Carbon dioxide and acetone mixtures as refrigerants for industry heat pumps to supply temperature in the range 150–220ºC, Energy, Volume 269, 126821.

Höhler F, Deschermeier R, Rehfeldt S, Klein H, 2018. Gas solubilities of carbon dioxide in methanol, acetone, mixtures of methanol and water, and mixtures of methanol and acetone. Fluid Phase Equil; 459:186 – 95.

Huang X, Zhang J, Haglind F, 2022. Experimental analysis of condensation of zeotropic mixtures from 70 ◦ C to 90 ◦ C in a plate heat exchanger. Int J Refrig.

Lemmon EW, Bell IH, Huber ML, McLinden MO, 2018. NIST standard reference database 23: reference fluid thermodynamic and transport properties-REFPROP, version 10.0. Gaithersburg: National Institute of Standards and Technology, Standard

Reference Data Program; 2018.

Olsson O, Schipfer F, 2021. Decarbonizing industrial process heat: the role of biomass. IEA Bioenergy.

Ramírez-Ramos GE, Zgar Y, Salavera D, Coulier Y, Ballerat-Busserolles K, Coronas A, 2021. Vapor-liquid equilibrium, liquid density and excess enthalpy of the carbon dioxide+acetone mixture: Experimental measurements and correlations, Fluid Phase Equilibria, Volume 532, 112915.

Roskosch D, Venzik V, Schilling J, Bardow A, Atakan B, 2021. Beyond Temperature Glide: The Compressor is Key to Realizing Benefits of Zeotropic Mixtures in Heat Pumps. Energy Technology, 2000955.

Thiel GP, Stark AK, 2021. To decarbonize industry, we must decarbonize heat. Joule; 5:531 – 50.

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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