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Proceedings of the 7th International Seminar on ORC Power Systems

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pocketORC: A BROWSER-BASED CALCULATOR FOR TEACHING ORGANIC RANKINE CYCLE POWER SYSTEMS

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ABSTRACT

This paper presents a steady-state design model for an organic Rankine cycle (ORC) power plant that is completely web-browser based and does not rely on any external libraries (e.g., for the computation of thermodynamic properties). This means the tool can be easily accessed by students via any electronic device with a web browser and used as a teaching aid to teach basic principles relating to ORC power systems. Therefore, ORC power cycles can be introduced interactively without requiring any programming knowledge or the distribution and installation of source files. This allows ORC power systems to be introduced earlier in the curriculum, and to a wider variety of students, than might otherwise be possible. The current version of the model combines the Peng-Robinson equation of state with a thermodynamic model of a recuperated ORC system and discretised heat exchanger sizing models. The model is written in the Python programming language and the PyScript framework is used to call Python code directly from HTML. The user can vary cycle variables such as the condensation temperature, pressure ratio, degree of superheat, recuperator effectiveness and heat-source temperature drop via the graphical-user interface which returns key indicators of cycle performance such as thermal efficiency and power output amongst others. The tool enables single-point calculation and parametric studies of a single variable and includes introductory self-paced lessons. This allows students to develop an understanding of the influence of different cycle variables on cycle performance. This paper provides an overview of the tool and its capabilities, alongside discussing its potential role as a teaching aid to support the introduction of ORC power systems into the curriculum.

1 INTRODUCTION

Over recent decades there has been a growing interest in the organic Rankine cycle (ORC) as a suitable power cycle for the conversion of low-temperature heat into power. Specifically, the ability of the cycle to convert low temperature heat from renewable sources, such as solar thermal and geothermal, alongside industrial waste heat, into power means the cycle could be an integral part of future clean energy infrastructure. Alongside this, there is a growing acknowledgement about the importance of heat pumps in the electrification and decarbonisation of heat production, and ORC systems and heat pumps share several similarities in terms of the underlying scientific fundamentals.

As such, there is a clear need for engineers and energy professionals who develop an understanding of these technologies during their education who then have the skills necessary to work with these technologies in their professional careers. Unfortunately, the complex thermodynamic nature of organic fluids means it can be difficult to fully address the underlying physics within traditional teaching activities. For example, a traditional Brayton cycle can be easily modelled using a simple system of equations that can be formulated based on the ideal gas law. This means a relatively simple system of equations can be easily solved by students, and trends in performance parameters, such as efficiency, with key cycle variables can be readily established. In comparison, for an ORC system, or indeed a steam Rankine cycle, the more complex thermodynamic behavior means such activities can only be carried out if tabular thermodynamic properties are provided, and a rather tedious analysis procedure adopted. This may typically mean that when carrying out hand calculations in class only single-point calculations can be done, whilst trends can be shown to students but not easily replicated.

The challenge of introducing these cycles operating with more complex thermodynamic fluids into the curriculum can be aided with the use of computational modelling tools. This could include using standard software such as Excel with a suitable add-in or using more specialist open-source or commercial software. Within the ORC community there have been a number of open-source tools that have been developed for ORC power cycles in mind, which includes, amongst others, CoolProp (Bell et al., 2014) for predicting fluid properties, ThermoCycle (Quoilin et al., 2014) and ThermoPower (Casella & Leva, 2003) for dynamic modelling in Modelica, the ORC modeling kit (Dickes et al., 2016) for steady state simulation, and NiceProp (Giuffre & Pini, 2022) for characterising the non-ideal gas dynamics of organic fluids. However, many of these tools are perhaps aimed more at other researchers, alongside post-graduate students that may be completing MSc or PhD research projects in the area. They also require downloading and installing source code, and therefore a degree of fluency in programming. As such, these tools may not be that suitable for undergraduate students, or indeed post-graduate students who may have an interest in renewable and sustainable energy technologies and are enrolled onto taught courses related to energy policy, economics or business management. These students stand to benefit by learning about ORC systems, but may lack familiarity or confidence in computational modelling or programming. Of course, example models could be setup in commercial modelling software, such as Simulink or Aspen as examples, but this requires a certain level of literacy with those tools, alongside timetabled computer labs where students have access to licensed software.

This paper introduces a new steady-state modelling tool for ORC power systems, named pocketORC, that operates straight from the web browser and relies purely on data entry via a web form. This means topics related to the design and simulation of ORC power systems can be introduced in the curriculum, and students can carry out cycle simulations in real time using any electronic device with access to the internet. As such, the effect of the working fluid, and trends in key performance parameters with different cycle variables can be easily assessed in real time. This paper is structured in three parts. Firstly, an overview of the tool is provided in Section 2, which includes details on how the tool has been developed and a summary of its capabilities. This is followed by an overview of the underlying mathematical modelling in Section 3. In the third part of this paper, examples of how this tool could be used to introduce ORC power systems into the curriculum are discussed. 54

The tool can be accessed via the following link: https://martintwhite.github.io/pocketORC/.

2 OVERVIEW AND IMPLEMENTATION

pocketORC is a steady-state simulation tool for ORC systems that is based on in-house Python scripts that have been developed by the author for predicting the thermodynamic properties of organic fluids and for simulating ORC power systems. The inputs required to run the pocketORC tool, alongside the outputs generated via the tool, are integrated within a graphical-user interface written in HTML. To call the Python scripts directly from HTML, the recently developed open-source PyScript framework (Anaconda, 2022) is employed. This enables the Python scripts to be uploaded onto the web server and to be run directly from the browser. As such, no installation of any local files is necessary.

An overview of the capabilities of the model is provided in Figure 1. For several fixed inputs that define the intended heat source and heat sink, alongside component parameters, the user can vary the working fluid and six different cycle variables to vary the performance of the system. The outputs of the model include the power output, mass-flow rate, first- and second-law efficiencies alongside the pinch points and UA requirements of the heat exchangers. These are reported in tabular form, alongside a temperature-entropy diagram of the resulting cycle. The tool can simulate a range of different cycle variants, including simple subcritical cycles, recuperated cycles, transcritical cycles and trilateral or partially evaporating cycles. Currently, three working fluids can be modelled, namely R1233zd(E), *n*-pentane and hexamethyldisiloxane (MM), although additional fluids can be easily added in the future.

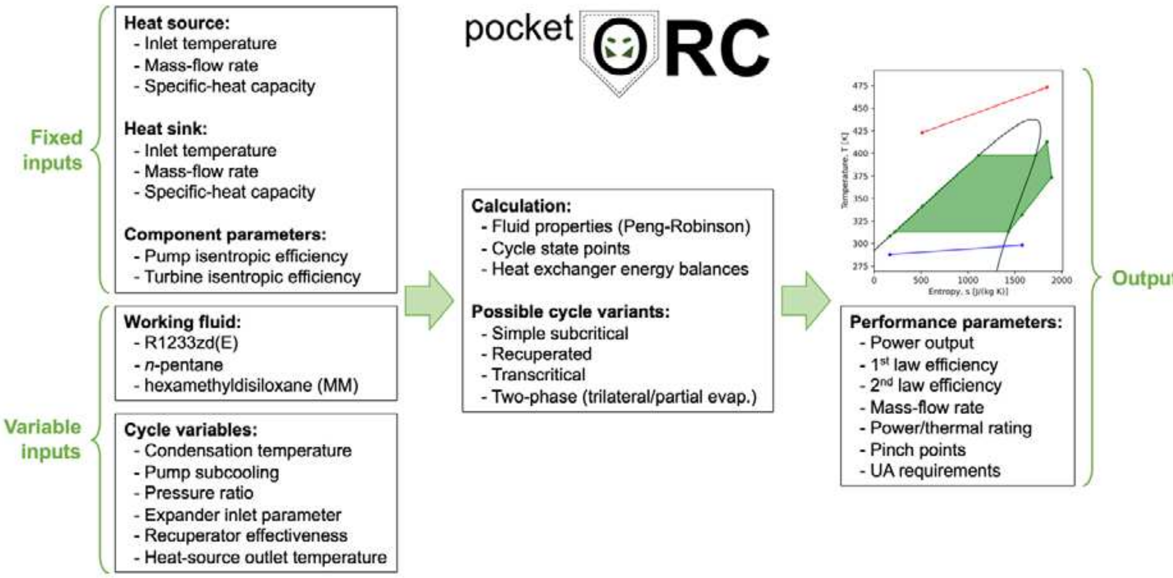

Figure 1. Overview of the modelling capabilities of pocketORC.

3 MATHEMATICAL MODELLING

This section summarises the underlying mathematical modelling that takes placed under the hood of pocketORC. To an experienced researcher working with ORC systems, it is anticipated that this theory is very familiar and therefore the precise mathematical details will not be provided here. Instead, a short summary of the approach is provided, alongside supporting justifications. A more detailed description of the underlying calculations will be made available on the website. 55

3.1 Thermodynamic properties

Thermodynamic properties of the working fluid are calculated using an in-house thermodynamic module based on the Peng-Robinson equation that has been developed by the author in a previous work (White & Sayma, 2018). Although the Peng-Robinson equation of state is not as accurate as state-of-the-art multi-parameter equations of state, such as those implemented within software packages such as CoolProp and REFPROP, the Peng-Robinson equation of state is known to provide reasonable predictions for fluid properties, particularly in the vapour-phase region. In the previous work, a maximum deviation in power output of 5.9% was found between cycle calculations completed using the Peng-Robinson equation of state and using REFPROP (White & Sayma, 2018). This level of accuracy is considered sufficient for a tool whose primary purpose is teaching. More importantly, the in-house module is simple and is uploaded to the web server as a single python script which can be run directly using PyScript. The module includes all the necessary calculations for modelling thermodynamic cycles, including the prediction of saturation properties at fixed temperature or pressure and the prediction of single-phase properties based on temperature-pressure, pressure-enthalpy, and pressure-entropy flash calculations. Working fluids are defined based on six fluid parameters, including the critical temperature, critical pressure, acentric factor, and the coefficients for a second-order polynomial describing the variation in ideal-specific heat capacity with temperature.

3.2 Thermodynamic cycle modelling

The thermodynamic cycle model is largely based on cycle modelling activities previously completed by the author (White & Sayma, 2019, White 2021). The cycle is assumed to operate under a steady-state and no heat losses or pressure drops are considered. The model can be used to simulate different cycle architectures, including recuperated and transcritical cycles, alongside cycles operating with two-phase expansion. The heat source and heat sink are both modelled as fluid streams with a fixed specific-heat capacity, where the inlet temperature, mass-flow rate and specific-heat capacity of each stream are model inputs. The pump and turbine are modelled with a fixed isentropic efficiency. All heat exchangers are modelled as counter-flow heat exchangers using a discretised approach to determine the fluid temperature profiles. The log-mean temperature difference is then used to determine the total UA value (i.e., product of overall heat transfer coefficient U and heat exchanger surface area A) for each heat-transfer region, namely preheating, evaporation, superheating, precooling, condensation, subcooling and recuperation.

For a fixed heat source and heat sink, alongside fixed isentropic pump and turbine efficiencies, there are six variables that can be used to adjust the performance of the cycle. These are: the condensation temperature; the degree of subcooling at the pump inlet; the pressure ratio; the expander inlet parameter; the recuperator effectiveness; and the heat-source outlet temperature. All of these have standard definitions, except for the expander inlet parameter, x, which is used to enable cycles with single- and two-phase expansion to be modelled using a single parameter (White, 2021). If $x < 1$, then x defines the expander inlet vapour quality, otherwise it determines the expander inlet temperature from:

$$T = T_{\mathrm{ev}} + (x - 1)(T_{\mathrm{hi}} - T_{\mathrm{ev}}) \quad (1)$$

where T is the expander inlet temperature, T_{ev} is the evaporation temperature and T_{hi} is the heat-source inlet temperature. Thus, by allowing x to range between 1 and 2 it is possible to move the expander inlet condition from being saturated vapour (x = 1) to an expander inlet temperature that equals the heat-source inlet temperature (x = 2).

For a given set inputs, the model returns first- and second-law efficiency, the working-fluid mass-flow rate, the power rating or thermal load of each component, alongside the pinch-point temperature difference and UA value for each heat exchange process.

4 USAGE AS A TEACHING TOOL

4.1 Single-point performance calculation and parametric studies

In the first instance, pocketORC can be used as a single point calculator, in which, for a given set of fixed parameters and inputs, the tool calculates the performance of the cycle. The output of this calculation is a table that reports the key performance indicators alongside a temperature-entropy diagram of the cycle with the heat-source and heat-sink temperature profiles superimposed. Thus, based on an understanding of how different cycle variables influence performance, it is possible to carry out a manual iterative process in which the cycle can be optimised for a defined heat source and heat sink. In this capacity, pocketORC is a useful tool for any ORC practitioner looking to get an idea of the achievable performance from an ORC operating within a given application. A typical output from a single-point calculation completed using pocketORC is shown in Figure 2.

The second feature of pocketORC is the ability to carry out single-variable parametric studies. Any one of the six cycle variables can be selected as the parametric variable and a minimum and maximum value can be specified. Using those inputs, pocketORC creates an array of 10 input values ranging from the minimum to the maximum with a constant step and reports the variation in cycle performance parameters in the form of a table. The resulting data can be readily copied and pasted into a spreadsheet or similar program for further post processing if necessary. A typical output from a parametric study completed using pocketORC is shown in Figure 3.

4.2 Introductory lessons into ORC technology

Alongside the single-point and parametric calculators, pocketORC also includes lessons that are available on the website and which students can work through at their own pace. These lessons combine a qualitative explanation of important concepts with interactive plots which are again written in Python and interfaced with the website via PyScript. The aim of these lessons is not to delve into detail regarding the underlying mathematical calculations, but instead to build up a working model of an ORC power system. Through this, the key cycle variables and fixed parameters considered within the calculator are introduced. It is assumed that before starting these lessons, the student already has some familiarity with important concepts such as thermodynamic state variables (i.e., temperature, pressure, density, enthalpy, entropy) and the general operating principle of a closed-loop power cycle, such as the steam Rankine cycle.

Single cycle study

Having now selected your set of variables, it's time to see how the cycle performs. Hit the button below to find out. The results in the table summarise key performance metrics, as well as the work or thermal load of each component. The UA values are an indicator of the heat exchanger requirements and the pinch points indicate the minimum temperature differences in each heat exchange process.

Run single study

Eta (cycle) [%]	Eta (exergy) [%]	Mass flow [kg/s]	Net [kW]	Pump [kW]	Turbine [kW]	Heater [kW]	Cooler [kW]	Recup. [kW]	UA (hot) [kW/K]	UA (cold) [kW/K]	UA (rec.) [kW/K]	Pinch (hot) [K]	Pinch (cold) [K]	Pinch (rec.) [K]
17.496	29.082	0.148	12.247	0.499	12.746	70.000	57.753	14.200	2.582	3.259	0.635	12.069	12.095	17.510

It is also useful to view the cycle on a temperature-entropy diagram. In the below figure the green region indicates the state points of the working fluid throughout the cycle. Superimposed onto that are the heat source (red) and heat sink (blue) temperature profiles.

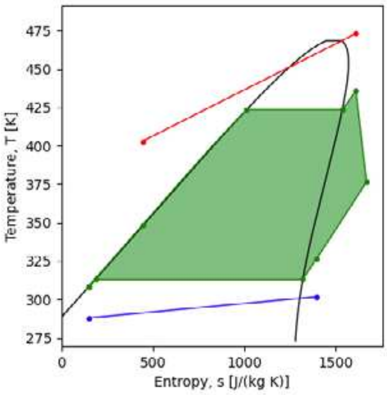

Figure 2. Example output from pocketORC for a single-point performance calculation.

Parametric study

Want to understand how the different cycle variables can influence performance? Then pick a variable from the drop-down box below, alongside the minimum and maximum values you want to consider, and hit run to populate the table. All other variables are assumed constant as defined earlier.

Parametric variable: Pressure ratio [-]

Minimum value: 2
Maximum value: 20

Run parametric study

Param. var.	Eta (cycle) [%]	Eta (exergy) [%]	Mass flow [kg/s]	Net [kW]	Pump [kW]	Turbine [kW]	Heater [kW]	Cooler [kW]	Recup. [kW]	UA (hot) [kW/K]	UA (cold) [kW/K]	UA (rec.) [kW/K]	Pinch (hot) [K]	Pinch (cold) [K]	Pinch (rec.) [K]
2.000	5.412	8.995	0.173	3.788	0.045	3.833	70.000	66.212	11.254	0.726	4.103	0.636	67.531	9.905	14.107
4.000	10.289	17.102	0.163	7.202	0.127	7.330	70.000	62.798	12.125	0.970	3.746	0.630	50.563	10.770	15.252
6.000	12.881	21.410	0.158	9.017	0.205	9.222	70.000	60.983	12.787	1.207	3.566	0.629	39.097	11.241	16.039
8.000	14.586	24.245	0.154	10.210	0.280	10.490	70.000	59.790	13.293	1.465	3.450	0.630	30.301	11.556	16.609
10.000	15.819	26.295	0.151	11.073	0.354	11.428	70.000	58.927	13.685	1.761	3.368	0.631	23.155	11.784	17.024
12.000	16.759	27.856	0.149	11.731	0.427	12.158	70.000	58.269	13.983	2.121	3.306	0.633	17.169	11.959	17.319
14.000	17.496	29.082	0.148	12.247	0.499	12.746	70.000	57.753	14.200	2.582	3.259	0.635	12.069	12.095	17.510
16.000	18.084	30.059	0.147	12.659	0.571	13.230	70.000	57.341	14.343	3.224	3.222	0.637	7.694	12.201	17.607
18.000	18.554	30.841	0.146	12.988	0.643	13.631	70.000	57.012	14.412	4.264	3.192	0.639	3.948	12.284	17.612
20.000	18.927	31.460	0.145	13.249	0.715	13.964	70.000	56.751	14.402	7.042	3.170	0.641	0.786	12.345	17.522

Figure 3. Example output from pocketORC for a parametric study considering pressure ratio.

The lesson structure for pocketORC is provided in Table 1, which summarises the topic of each lesson and the parameters introduced. Examples of the interactive plots generated within the first three lessons are provided in Figure 4. For example, the content of Lesson 1 focusses on introducing the first two variables which control the evaporation and condensation processes, namely the condensation

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temperature and pressure ratio, and the corresponding interactive plot enables the user to see these in the temperature-entropy plane (Fig. 4(a)). This is extended to the variables controlling the pump and expander inlet conditions in Lesson 2, as shown in Fig. 4(b). At this point an ideal cycle with isentropic compression and expansion processes can be defined and the cycle efficiency can be evaluated, which is the first topic of Lesson 3 (Fig. 4(c)). This is extended to real cycles, before recuperation, heat exchanger energy balances and alternative cycles are introduced in Lessons 4, 5 and 6 respectively.

Table 1: Summary of the lesson structure for pocketORC.

#	Title	Topics covered	Parameters introduced
1	Saturated properties	• Saturation properties • Evaporation and condensation	• Condensation temperature • Pressure ratio
2	Single-phase properties	• Subcooled and superheated properties • Pump and expander inlet conditions	• Degree of pump subcooling • Degree of expander superheating
3	Ideal and real cycles	• Ideal cycle • Real cycle	• Cycle efficiency • Pump isentropic efficiency • Expander isentropic efficiency
4	Recuperation	• Recuperated cycles	• Recuperator effectiveness
5	Heat exchangers	• Heat source modelling • Heat sink modelling	• Heat source inlet temperature, outlet temperature, mass-flow rate • Heat sink inlet temperature, outlet temperature, mass-flow rate • Net power output
6	Alternative cycles	• Transcritical cycles • Two-phase expansion	• Expander inlet parameter

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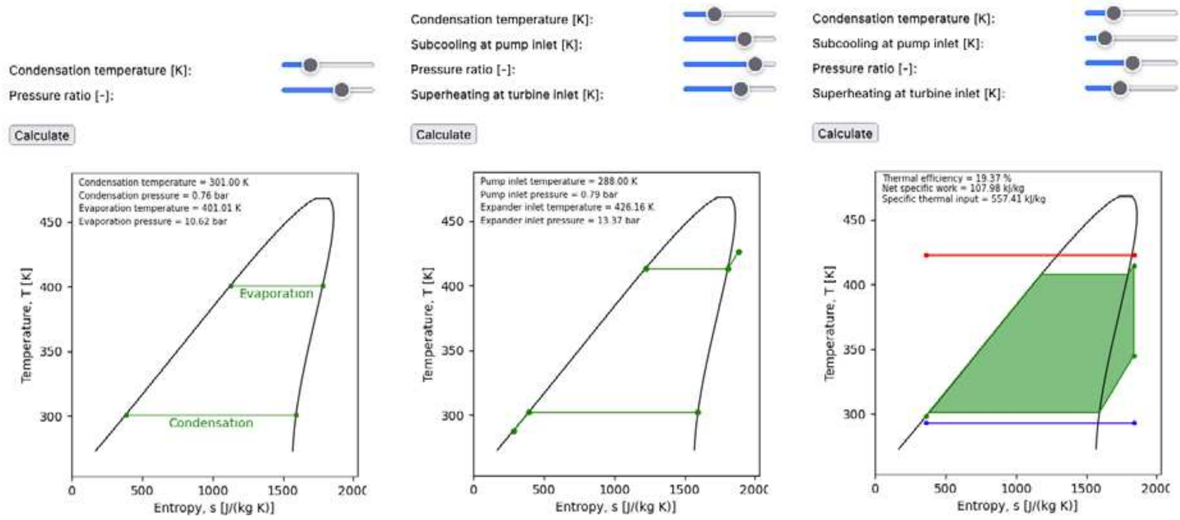

(a) (b) (c)

Figure 4. Example interactive plots created within Lessons 1, 2 and 3 of pocketORC.

4.3 Wider integration within the curriculum

It is intended that the available lessons, and the pocketORC calculator itself, provide a useful set of tools to introduce ORC power systems into the curriculum. Whilst these can be used as a self-paced introduction into ORC systems, several additional teaching activities can also be envisioned.

In the first instance, the tool can be used to set students an open design exercise, which could involve designing an ORC system for a particular application. In this scenario, a specific application could be introduced (i.e., geothermal, solar-thermal, waste-heat recovery) and defined in terms of an available heat source and heat sink. The students are then tasked with designing an optimal system for that application. This could be left open-ended with students free to establish optimal values for all six variables for a given working fluid, or the scope could be narrowed by fixing the heat source outlet temperature, considering simple cycles without recuperation, and providing recommendations for the degree of subcooling. Thus, simple parametric studies concerning the remaining three cycle variables can be completed by the students.

More widely, an ORC system comprises of several engineering components which themselves are introduced within the curriculum. More specifically, ORC systems are reliant on pump and turbines, alongside heat exchangers, which are components introduced within taught modules on turbomachinery and heat transfer respectively. Thus, pocketORC can be used as an aid to introduce the design of these components for ORC power cycles. In this capacity, pocketORC can be used by students to define the boundary conditions that are used in the subsequent design of these components. For example, at the time of writing the author is planning on introducing a project relating to the design of an air-cooled condenser for ORC power plants within a master's level module focused on heat transfer applications. Another possibility would be to ask the students to take the system-level analysis beyond the calculations completed within the tool. This could include evaluating a particular ORC system design from a techno-economic perspective, which would involve translating the outputs from pocketORC, such as the component power ratings or heat exchanger UA values, into estimated costs based on published cost correlations. In this capacity, ORC technology can be introduced to students from a broader energy background who may be interested in these economic factors.

Finally, it is worth noting the similarities in the analysis of an ORC and that of a heat pump system. Thus, the infrastructure used to build pocketORC could be easily extended to introduce a similar calculator for heat pump systems. This extension is currently planned for later in the year. This could open the possibility of introducing heat pump systems in a similar fashion to ORC systems, which could ultimately allow students to compare different technical options for a given heat source. For example, for a given waste heat stream students could be asked to evaluate and compare the performance of an ORC or heat pump system and then select the most viable option.

5 CONCLUSIONS

The wider implementation of ORC power systems requires energy professionals that have the necessary technical skills to design, simulate and evaluate the feasibility of the technology in different application areas. Principally, this knowledge should be developed within the taught curriculum of engineering and related courses. However, the high degree of scientific literacy, and potentially computing literacy, required to design and simulate ORC power cycles can hinder the extent to which the topic can be introduced in taught courses. With this is mind, this paper has introduced a new web-browser based calculator for ORC power systems that is suitable for a wider student audience. It is intended that the calculator, alongside the supporting self-paced lessons, can aid with the introduction of ORC technology at an earlier stage within the curriculum and provide a useful tool for ORC practitioners alike. Alongside providing an overview of the tool and its implementation, this paper has summarised its capabilities and put forward a vision of how it could be used as an additional teaching aid. This includes supporting open design exercises, designing power cycle components, and potentially helping to benchmark the technology against other technologies from a techno-economic perspective.

NOMENCLATURE

A	heat exchanger area	(m^2)
T	expander inlet temperature	(K)
T_{ev}	evaporation temperature	(K)
T_{hi}	heat-source inlet temperature	(K)
U	overall heat transfer coefficient	(W/m^2 K)
x	expander inlet parameter	(-)

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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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