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# Organic Rankine cycle design and performance comparison based on experimental database

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## HIGHLIGHTS

- An open-access database of ORC experiments is presented and released.
- ORC main parameters are discriminated and harmonized in the database frame.
- A selection of simplified ORC thermodynamic performance criteria is proposed.
- Database analysis shows actual Organic Rankine Cycle state-of-the-art performances.
- A statistical method for ORC performances analysis and comparison is introduced.

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## ABSTRACT

The Organic Rankine Cycle (ORC) is a technology commonly used for low-grade thermal energy conversion in electricity. This technology is mature for large power scale and last research focused on small scale units for domestic or onboard applications. This paper presents an extensive open-access database of more than 100 ORC experiments collected from about 175 scientific literature references. Data harmonization and database frame are presented. Clear and consistent components and ORC performance criteria are proposed and applied to the data set of various ORC. An overview of the ORC experimental state-of-the-art is displayed and major trends are drawn. Efficiency of key components such as expanders and pumps are analyzed and used for ORC parametric optimization case study. Correlations of some parameters with ORC performances are statistically investigated, performance improvement of novel fluid or cycles is evaluated.



## 1. Introduction

The energy sector is facing major challenges in the upcoming century as energy demand, driven by the world population and economic growth, is rising and its major impact on the global warming issue needs to be addressed. Among the solutions to overcome these challenges, renewable energies and process energy efficiency could be partially fulfill by the use of the Organic Rankine Cycle (ORC) technology.

The organic Rankine cycle is a heat to power conversion technology used since the 19th century to transform energy from a variety of sources such as geothermal, solar, biomass or waste heat recovered (WHR) from the industrial process or internal combustion engines (ICE). Current range of commercial ORC goes from 10 kWe to 10 MWe converting heat sources between 80 °C and 300 °C, but this range is extending as new application are developed such as ocean thermal energy conversion, micro-CHP (combined heat and power) or vehicle engine heat recovery [1–3].

The organic Rankine cycle is derived from classic Rankine cycle, the pressurized working fluid is heated and vaporized by the heating fluid, expands in an expander to produce mechanical work, condensates at low pressure by the cooling fluid and is pumped back to close the cycle. The major difference with the classic Rankine cycle is the use of organic fluids as working fluid instead of water, the working fluid can be selected according to the heat source and usage [4].

Researches on ORC increased in the last decades, focusing on design optimization, fluid selection, expander technologies or

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**Nomenclature**

| | |
|---|---|
| $c_p$ | specific heat capacity |
| E | exergy |
| e | specific exergy |
| h | specific enthalpy |
| I | electric current |
| m | mass flowrate |
| P | pressure |
| Q | heat power |
| s | specific entropy |
| T | temperature |
| U | electric tension |
| V | volume flowrate |
| v | specific volume |
| W | power |

*Greek symbols*

| | |
|---|---|
| $\Gamma$ | torque |
| $\Delta$ | difference |
| $\varepsilon$ | exergetic efficiency |
| $\eta$ | energetic efficiency |
| $\xi$ | fluid saturated vapor slope |
| $\rho$ | Spearman's coefficient |
| $\Phi$ | dissipations |
| $\varphi$ | electric phase |
| $\Omega$ | rotating speed |

*Subscripts*

| | |
|---|---|
| ad | adiabatic |
| aux | auxiliaries |
| el | electric |
| eva | evaporator |
| exp | expander |
| gen | generator |
| hf | hot fluid |
| hr | heat recovery |
| hy | hydraulic |
| in | inlet |
| ind | indicated |
| int | internal |
| is | isentropic |
| max | maximum |
| me | mechanic |
| out | outlet |
| pp | pump |
| rec | recovery |
| sup | supplied |
| wf | working fluid |
| 0 | reference |
| II | second law (efficiency) |

*Acronyms*

| | |
|---|---|
| AC | Alternative Current |
| BWR | Back Work Ratio |
| CHP | Combined heat and power |
| DC | Direct Current |
| HEx | Heat Exchanger |
| HF | Hot Fluid |
| ICE | Internal Combustion Engine |
| IHE | Internal Heat Exchanger |
| ORC | Organic Rankine Cycle |
| VSD | Variable Speed Drive |
| WHR | Waste Heat Recovery |

dynamic control. To support those research, many experimental benches were built for validation or models data-feeding purposes. Colonna et al. [1], Quoilin et al. [2] and Tchanche et al. [5] presented general review of the Organic Rankine Cycle technology history and future, typical industrial applications and market trends as well as ORC key components' types and issues such as expander, working fluid, heat exchanger or pump. Rahbar et al. [6] proposed a similar review with a focus on small power scale (5 kW to 5 MW), while Vélez et al. [7] proposed a focus on the economic and market trends of the ORC technology. Other reviews focused on ORC working fluid characteristics and selection criteria [4,8,9], or expander technologies, performances and modeling [4,10,11]. Lecompte et al. [12] proposed an exhaustive review of ORC architectures and advanced cycles such as recuperated, regenerative, flash or multi-pressure. Previous reviews presented a qualitative state of the art around the ORC technology. However, they present a given time picture, with a limited number of experimental references.

In the present paper, an open-access and collaborative database of ORC experimental work is presented in Section 2. This database aims to be as exhaustive as possible and extensive as it can be continuously updated with new references. It allows an objective review of ORC experiments through a factual and quantitative survey. Each ORC bench is tested in a different environment (heat and sink sources), for different objectives and analyzed by different methods. It results an addition of measurements, methods and definitions uncertainties on the cycle efficiency while the relative performance difference between two fluids, expander or cycle architecture can be rather small. Therefore, one of the major challenges to perform an objective comparison is to propose a clear data discrimination and classification, as well as harmonized performances criteria for both components and cycle that might be applied to the present database. Lecompte et al. [12] already proposed a number of clear ORC performance criteria using both energetic and exergetic analysis for open and closed heat sources [13], while Branchini et al. [14] proposed advanced indexes such as expander volumetric expansion ratio or total heat exchangers surface as size/economic parameters.

ORC design & parametric optimization is used at the early stage of projects to evaluate the potential of the ORC implementation. Contrary to advanced ORC modeling [15], parametric study uses mostly constant isentropic efficiency for pump and expander performances, but provides few references to justify the selected efficiency, while it has a large impact on the optimization process [16]. In the literature, expander isentropic efficiency ranging from 70 to 85% are used and pump isentropic efficiency from 60 to 90% with heat exchanger pinch point from 5 to 10 K [17–20]. The present work and database provides a number of experimental references for components efficiency, especially at small-scale. Examples of parametric optimization will be performed and presented in Section 3.

Many research on ORC focus on working fluids, expander and cycle architecture. Out of the numerical modeling evaluation of performance improvement, experimental validation can be complex. A common way is to compare different cases with the same test bench. Some authors compared different expanders with the same fluid and set-up [21–25]. Other compared different fluids or mixture proportions on the same ORC [26–36]. Some studies compared simple configuration with recuperated configuration