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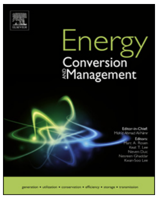

Review

Review of Organic Rankine Cycle experimental data trends

Byung-Sik Park[a,b,*], Muhammad Usman[a,b,c], Muhammad Imran[a,b,d], Apostolos Pesyridis[c]

[a] *Korea University of Science & Technology (UST), 217 Gajeong-ro, Yuseong-gu, 34113 Daejeon, South Korea*
[b] *Korea Institute of Energy Research (KIER), 152 Gajeong-ro, Yuseong-gu, 34129 Daejeon, South Korea*
[c] *Centre of Advanced Powertrain and Fuels (CAPF), Department of Mechanical, Aerospace, & Civil Engineering, Brunel University London, Uxbridge, UB8 3PH London, United Kingdom*
[d] *Section of Thermal Energy, Department of Mechanical Engineering, Technical University of Denmark (DTU), Niks Koppels Alle, Building 403, 2800 Kgs. Lyngby, Denmark*

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ABSTRACT

Organic Rankine Cycle (ORC)-based systems are being extensively investigated for heat-to-electric power conversion from various sources, such as biomass, waste heat recovery, concentrated solar thermal and geothermal. The ORC technology has a promising future as it helps to meet energy requirements, arguably with a minimal environmental impact. This work summarizes the current state-of-the-art of actual i.e., experimental ORC system performance, derived from a comprehensive analysis of the most significant, relevant and up-to-date experimental data published in scientific literature. A survey of more than 200 scientific works is scrutinized according to specific selection criteria and data is extracted to develop a database containing thermodynamic cycle information along with component-level performance information. Performance trends are discussed and addressed as functions of first principles. One of the least surprising results indicate that the performance follows economies of scale. More revealing is the fact that the Organic Rankine Cycle conversion efficiency (mechanical to electrical) was around 70%. Furthermore, it becomes clear that there is a large gap between research and development for source and sink temperature differences above 150 °C. In general, the overall heat to electrical power conversion efficiency was around 44% of the Carnot cycle efficiency of the cycle. A host of other relevant thermodynamic parameters are cross-compared, as well as compared to theoretical results, allowing a level of practical ORC system design target homologation to be achieved which is useful for the engineer as well as the scientist in the design of ORC components, systems as well as advanced cycles.

1. Introduction

The future energy demands of the ever-increasing global population require efficient utilization of current energy resources as well as the development of new renewable energy solutions. Organic Rankine Cycle (ORC) based power systems have gained significant popularity in last two decades due to their adaptability to utilize a wide range of energy sources [1]. ORC technology is being rapidly developed for improving the overall efficiency of conventional energy conversion systems. They can be effectively used for waste heat recovery (WHR) from internal combustion engines (ICE) exhaust [2–4] and also from industrial processes [5,6]. The recovered heat energy, which otherwise would be released to the environment can now be converted to electricity, thus providing financial benefit along with a greenhouse gas emission reduction contribution [7,8]. ORC systems are also well known for their application in the heat to power conversion from biomass [9,10], concentrated solar thermal (CST) [11,12], geothermal [13,14], ocean thermal energy conversion (OTEC) [15,16], and combined heat and power (CHP) systems [17,18].

Apart from the type of application, ORC systems are further classified based on technical parameters, such as their power capacity, heat source temperature, and configuration. In general, the transition boundaries of temperature zones and scales were not sharply marked but recent works suggested generally acceptable limits for these boundaries which are presented in Table 1 adapted from [19].

Basic ORC power systems are composed of four major components, evaporator, expander, pump and condenser. Organic working fluid is heated under pressure and converted to high-pressure vapor, the high-pressure vapor then passes through expander which extracts the energy from fluid and converts to mechanical energy which is often converted to an electrical energy by the attached generator. The low-pressure vapor then flows to a condenser which removes heat to a low-

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[*] Corresponding author at: Korea Institute of Energy Research (KIER), 152 Gajeong-ro, Yuseong-gu, 34129 Daejeon, South Korea.
E-mail address: bspark@kier.re.kr (B.-S. Park).

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Nomenclature

BWR	back work ratio
CHP	combined heat and power
CST	concentrated solar thermal
ICE	internal combustion engine
ORC	Organic Rankine Cycle
OTEC	ocean thermal energy conversion
T	temperature
TIT	turbine inlet temperature

Subscripts

AV	average
CF	cooling fluid
cr	critical
elec	electric
evap	evaporator
exp	expander
HTF	heat transfer fluid
max	maximum
mech	mechanical
WF	working fluid

temperature sink fluid and condenses the vapors to the liquid phase. The low-pressure liquid working fluid is then pumped to the evaporator by the action of the pump to complete the cycle. Fig. 1a presents the most commonly adapted ORC configuration and Fig. 1b presents a relatively less common configuration which is often used when a large amount of heat can be recovered from de-superheating of working fluid after turbine exit.

The research and development of ORC technology are being exploited in multiple dimensions. Table 2 presents the few of the common of the research streams. The term "Organic Rankine Cycle" was initially looked up in titles only in Scopus [21] database and a total was obtained. The mentioned research streams in first column of Table 2 were added in search with "AND" conditions with "Organic Rankine Cycle" to output results which were presented as a ratio to initial results and described as normalized.

The ORC publication count has drastically increased in last decade to support the listed research streams in Table 2.

Apart from the mentioned works in Table 2, review articles have been regularly published in the field, to sum up, the state-of-the-art and general understanding of the ORC technologies. Hung et al. [1] presented a review back in 1997 and compared the efficiencies of ORCs using cryogenics such as benzene, ammonia, R11, R12, R134a and R113 as working fluids. The reported, isentropic fluids are most suitable to recover low-temperature waste heat. Chen et al. [52] presented a review of thermodynamic cycles and working fluids for conversion of low-grade heat to power. Screening of 35 working fluids was performed based on thermodynamic and physical properties, stability, environmental impact, safety and compatibility in 2010. Tchanche et al. [53] reviewed the potential of ORC application for low-grade heat to power conversion from various applications in the year 2011. A techno-economic market review was presented in the following year by [54] for low-grade heat to power conversion by ORC application. A review of ORC application for internal combustion exhaust waste heat recovery revealed in 2012 [55] that a potential economy improvement around 10% with modern refrigerants and advancements in expander technology exists. Bao and Zhao [56] presented a review of working fluid and expander selection for low and medium temperature ORCs in 2013. They identified a knowledge gap needs to be filled to know more about heat transfer characteristics, flammability and material compatibility of pure working fluids. They also concluded that the experimental researches of ORC are very limited and mostly focused on the build of renovated of expanders. Song et al. [57] presented a review specifically on the scroll expanders for ORC in 2014 and suggested scroll machines are popular for microscale ORCs because of few moving parts, reliability, compact structure and low noise levels. Lecompte et al. [20] reviewed ORC architectures for waste heat recovery in 2015. They discussed the ORCs with recuperators, regenerative ORCs, Organic flash cycles, trilateral flash cycles, zeotropic mixtures as ORC working fluids, vapor injector and reheat and cascaded cycles. Colonna et al. [19] performed a comprehensive review of ORC from the concept to current technology applications and outlook to the future in 2015. Systematic methods for working fluid selection and design, integration, and control of ORC system was review by [58] in the same year. Imran et al. [59] reviewed the volumetric expander options available for waste heat recovery applications in 2016. A review of the performance and operational aspects of expanders for small-scale ORC was presented in the same year [60]. Lion et al. [2] presented a review in 2017 and discussed ORC application for on-off highway vehicle heavy-duty diesel engine for waste heat recovery options from the exhaust gas, EGR, coolant circuit, charge air cooler and oil circuits. In the same year, Tocci et al. [17] presented a review on techno-economic aspects of small-scale ORCs and reported that working fluid selection and expander design are the bottleneck in the commercialization of ORC technology. Rahbar et al. [61] also presented a review on small-scale applications highlighting the common application in biomass, geothermal, waste heat recovery and OTEC.

It is notable that most of the review works have focused on small-scale applications, waste heat recovery, expander and working fluid selection. The aforementioned works have presented, the general state of the art, design modeling and implementations of proposed systems. The results of individual experiments were often summarized with the specific objectives in focus. The present work, however, focuses on a carefully developed experimental database to express state-of-the-art baseline performance parameter trends of ORC systems based on first principles. As such, the present work aim at supporting ORC researchers by providing an estimated baseline insight of performance prediction if they are using state-of-the-art equipment. This will allow them to achieve more ambitious performance targets as the component level performance trends, significant correlations and estimates of losses are provided in this work. Landelle et al. [62] discussed state-of-the-art performance of ORC systems as a function of source temperature and economy of scale in ORC technology, while the current work presents the quality of cycle achieved with specific heat sources temperatures along with the experimental performance outcomes. This work targeted experimental works which presented comprehensive thermodynamic

Table 1
Classification of ORC systems.

Max temperature in the cycle (°C)		Power capacity		Configuration	
Low	< 150	Micro	< 3kW	Saturated	Simple, regenerated
Medium	150–250	Mini	3–50 kW	Superheated	Simple, regenerated
High	> 250	Small	50–500 kW	Supercritical	Simple, regenerated
		Medium	0.5–5 MW	Superheated	Zeotropic
		Large	> 5MW		