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State of art on ORC applications for waste heat recovery and micro-cogeneration for installations up to 100kWe

John Besong Obi^{a,*}^a University of Trieste, Department of Engineering and Architecture, via A.Valerio 10, 34127, Trieste-Italy

Abstract

The growing cost for energy production and distribution as well as problems related to environmental pollution have induced an increasing interest in the research of alternative solutions and in particular innovative technologies capable of compromising energy production cost, optimization and guaranteeing environmental sustainability. One of the technologies of increasing interest in recent years is the Organic Rankine Cycle (ORC). These systems are generally suitable for the recovery of low grade heat at low pressure this is a major advantage of the system in terms of safety and management. Furthermore, they enhance simple operation, low maintenance, and the use of a working fluid that is environmentally friendly. This paper presents a comprehensive and current literature overview of micro generation systems up to 100kWe. A working fluid screening criteria has been discussed taking into account the environmental impact as well as the thermo-physical properties of various potential working fluids. From the analyses it emerges that the fluid most used in installed ORC systems is the R245fa also confirmed by means of a computational code developed for micro-systems of the size range. Components and expander selection has also been examined, the study reveals that the most suitable expander for the applications of these plant size ranges are the scroll for small installations and the vane or screw expanders for larger installations. Finally a detailed list of characteristics of both industrial and experimental prototype application is presented with references to their manufacturers.

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Keywords: distributed generation; waste recovery systems; ORC applications; expanders; working fluids; ORC modeling.

1. Introduction

The Steam Rankine Cycle remains the widest used technology for power generation and the Organic Rankine Cycle differs from it in the cycle working fluid [1], the working fluid in these cycles determines the type of technology to be applied; power generation or an energy recovery system [2]. Advantages of the ORC include low maintenance, favorable operating pressures and autonomous operation. Tchanche *et*

* Corresponding author. Tel.: +39-040-5583051; fax: +39-040-5583812.

E-mail address: johnbesong.obi@phd.units.it

al[3] underlined some advantages achievable from power plants operating with an organic fluid. Early system architecture and component lay-out are available in[4], a recent and extensive publication on system architecture is discussed in[5]. Several authors have documented on working fluid screening methods as in[6], a list of potential working fluids for ORC applications is also presented. Plant design specifications and financial aspects have been dealt with by Lecompte and Cayer [7] who also addressed performance parameters like expander isentropic efficiency, pinch point temperature differences as well as the heat source temperatures in [8] suggesting different common architectures. Studies on ORC expanders have been covered in[9], different expander types have been investigated including traditional expanders as well as the use of other devices like compressors. Trends in developing a dynamic ORC model is proposed by Quoilin [10]. Other recent studies on dynamic modeling and control strategy of ORC are presented in[11].

A summary of different potential working fluids and substances commercially available for small ORC is presented in this article and suggestions on their choice depending on the target application; a thermodynamic model for the target applications has also been developed. ORC applications and heat resources are also examined, some references are also provided on the degree of maturity of various applications, to conclude, reference installations and manufacturers are provided with indication of their working conditions.

| Nomenclature | | | |
|---------------------|---|--------------|-----------------------------------|
| CHP | Combined Heat and Power | CSHP | Combined Solar Heat and Power |
| EES | Engineering Equation Solver | ICE | Internal Combustion Engine |
| HVAC | Heating, Ventilation and Air Conditioning | HMDSO | Hexamethyldisiloxane |
| OMTS | Octamethyltrisiloxane | ORC | Organic Rankine Cycle |
| OTEC | Ocean Thermal Energy Conversion | RORC | Regenerative ORC |
| T_{cond} | Condensing temperature | SORC | Standard ORC without regeneration |
| WHR | Waste Heat Recovery | T_{evap} | Evaporation temperature |
| η_{th} | thermal efficiency | η_{exp} | expander efficiency |

2. Working fluids in ORC

The working fluid is very essential for the definition of the thermodynamic properties, economical and technical flexibility of the plant in every power cycle. The selection criteria and the choice of a suitable working fluid must satisfy the thermodynamic requirements, compatibility, cost and be environmentally friendly [12]. An interesting study on fluid selection is presented by Chen [13]. A recent study on ORC working fluids is provided by Guo [14], while in [15] the comparison on the thermo-physical properties for different working fluids is presented. In[16]it was showed that fluid mixtures improve the cycle performance. In [17] the advantages of fluid mixtures over pure fluids in terms of safety and volumetric efficiencies are discussed. Tchanche [3] presented a list of substances identified as potential working fluids suitable for different applications in the ORC technology, a comparison of the choice of working fluids in ORC systems for three different characteristics; the target destination, the temperature ranges of evaporation and condensation is presented in table1, a further analyses on fluid selection was performed by Jinliang [18];

Table 1 Potential working fluids for ORC applications elaborated from [19]

| Application | T_{cond} [°C] | T_{evap}[°C] | Considered fluids | Recommended fluids |
|--------------------|-----------------------------------|----------------------------------|---|-------------------------------------|
| WHR | 30-50 | 120 | R11, R113, R114 | R113 |
| n/a | 35-60 | 80-110 | Non-conventional working fluids | RC123, R124 |
| WHR | 30 | 150-200 | RC123, HFE 7100, benzene, Toluene, p-xylene | Benzene, Toluene, RC123 |
| ICE | 55 , 100 | 60-150 | H ₂ O, RC123, Isopentane, R245ca, R245fa, Butane, Isobutane, R152a | H ₂ O, R245ca, Isobutane |

| | | | | |
|------------|-------|---------|---|---|
| CHP | 90 | 250-350 | Butyl-benzene, propyl-benzene, ethyl-benzene, Toluene, OMTS, Ammonium, R123, PF5050 | Butyl-benzene |
| n/a | 40-60 | 220-350 | HMDSO, OMTS, HMDSO/OMTS | HMDSO/OMTS |
| Geothermal | 30 | 100 | Alkanes, Fluoro-alkanes, Ethers, Fluoro-ethers | RE133, R245, R600, R245fa, R245ca, R601 |
| Geothermal | 25 | 80-115 | Propylene, R227ea, RC318, R236fa, Isobutane, R245fa | Propylene, R227ea, R245fa |
| WHR | 25 | 100-210 | R113, R123, R245fa, Isobutane | R113 |
| Solar | 35 | 60-100 | Refrigerant | R152a, R600, R290 |
| Solar | 45 | 120-230 | H ₂ O, n-pentane | n-dodecane |
| WHR | 25 | 145 | H ₂ O, NH ₄ , butane, Isobutane, R11, RC123, R141B | R236A |
| WHR | 50 | 80-220 | R600a, R245fa, RC123, R113 | R113, RC123 |
| CHP | 50 | 170 | R365mfc, heptane, Pentane, R12, R141b, Ethanol | Ethanol |
| ICE- WHR | 76 | n/a | R124 R134a, R245fa, R600, R600a, R1234yf | R134a |
| ICE- WHR | 95 | n/a | R125, R143a, R218 | R134a |
| Geothermal | 30 | 150 | R1225yeZ, R1234yf, R1234zeE, R1234zeZ, R1234zf, R1225yeE, R1225zc, R1234yeE | R1234yf, R1225yeE |
| WHR | 20-35 | 150 | R245fa, R245fa/R152a, R245fa/R600a, R113/R245fa, R601a/R600a, R236ea | n/a |
| ICE_WHR | 35 | 96-221 | R134, R11, benzene | Benzene |
| WHR | n/a | 120 | R290, R600a, R601, R134a, R227ea, R245fa, R600a/R601, R290/R600a, R134a/R245fa | R600a/R601 |
| WHR | 27-87 | 327 | R245fa, R245ca, R236ea, R141b, R114, RC123, R113, R11, butane | R11, R141b, R113, RC123, R245fa, R245ca |
| WHR | n/a | 277 | R12, RC123, R134a, R717 | RC123 |
| Solar | 30 | 150 | n-pentane, SES36, R245fa, R134a | R245fa, R134a |

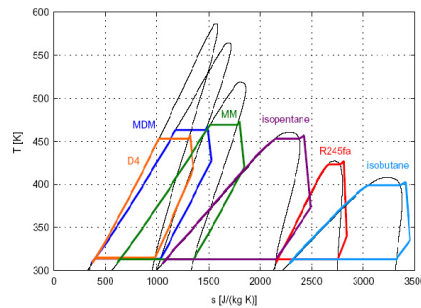


Figure 1. T-s diagram for some working fluids used in WHR

In order to investigate the ORC system performances parameters, a simulation model has been developed using the EES platform, the model will be described in a successive article under development. R245fa already abundantly discussed in literature has been confirmed to be a suitable working fluid candidate for waste heat recovery (low grade heat) systems, chosen according to the above mentioned selection criteria; heat source temperatures, system maximum pressure, safety, toxicity and the legislations imposed on the characteristics of a good working fluid. The results of a preliminary simulation have been provided as in figure 1, where it is visible the thermodynamic cycle diagram on the T-s plane for the 6 working fluids considered. The code has been validated using experimental data obtained from an available 2kWe ORC prototype driven by a scroll expander and running with R245fa, furthermore the code will be used for the assessment of system parameters for coupling the micro-generator with different heat sources as well as optimization of the prototype and system performances parameters computation for other working fluids.

3. Applications of ORC for small scale and distributed generations

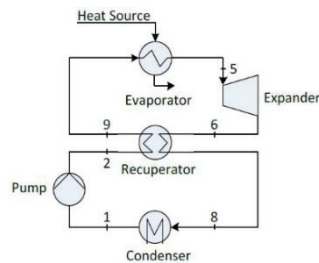


Figure 2 Configuration of an ORC facility with recuperator

A general description of the various potential uses of this technology is presented, with particular focus on small and medium sized applications, without ignoring some large installations. The cycle architecture of an ORC is simple, its' basic configuration is made of four main components: the feed pump, the evaporator, the expander and the condenser; however a recuperator (regeneration) can be integrated in the circuit as a preheater between the feed pump and the evaporator on one side and between the expander and the condenser on the other side as in figure 2.

3.1 Geothermal Energy

A geothermal system can be coupled to an ORC unit to serve as the heat source using as energy vector rain water for the heat extraction, the rain water is extracted at high pressures and temperature say up to 300°C and exploited for small and medium scale electric power generation [20]. Tchanche [3] underlined the total number of existing geothermal installations and the total energy capacity obtained from these installations, a classification of geothermal plants is also presented by Villani [21]. Small scale installations, for power range up to about 10 kW, can be cost-effective if and only if components with large production and market diffusion such as devices derived from the Heating, Ventilation and Air Conditioning (HVAC) field, are used [3].

3.2 Solar Energy

Solar systems provide a great opportunity for the coupling of an ORC since they are generally characterized with temperatures usually lower than 300°. The main advantages of a solar system have been summarized in [3], benefits offered by a solar ORC are found in [22]. Both flat and concentrated solar panels can be coupled with an ORC system, depending on the applications and the installations site: while flat plate collectors require a lower capital investment [23], concentrating collectors ensure a higher total amount of produced energy throughout the panel operating life, especially if equipped with sun tracking systems as featured by Delgado Torres and Garcia-Rodriguez in [24]. Wang [25] made a comparison between a flat plate and the evacuated tube type collectors in a solar ORC running with R245fa, and achieved a higher conversion efficiency with the evacuated tube collectors. In a successive article [26], he tested both pure substances and mixtures on an ORC prototype equipped with flat plate collectors. Jing [27] developed a simulation model of a solar ORC system with dedicated submodels for solar radiation, collectors behavior, and thermodynamic cycle performance. Kane *et al* [28] designed, built and optimized a mini-hybrid solar power system suitable for installation in remote areas of developing countries, the field tests confirmed the possibility of achieving acceptable performances with the prototype

3.3 Desalination systems

Water desalination coupled with an ORC offers notable benefits, the solar RO-ORC desalination

technology is widely studied today, aiming to reach the economic competitiveness and to design low cost systems suitable for applications in developing countries especially with harsh climate[28]. In order to reduce the environmental impact of a RO (Reversed Osmosis) desalination system, the power needed for pumping should be provided from renewable sources.

3.4 Biomass Power plants

Biomass is an abundant heat resource, although it presents enormous difficulties in transportation due to its low energy density, it is locally the most adapted for micro scale distributed CHP generation as reported in [29]. For the small size biomass CHP systems, coupling with combustion engines or ORC technologies is rapidly gaining considerable interests. In the second case, a typical system is made of a biomass feed boiler capable of burning solid fuels and an ORC module coupled through a thermal oil loop. The need for an intermediate heat transfer medium, which gradually cools down in the vapor generator provides a number of advantages such as; low pressure in the boiler, larger thermal inertia and lower sensitivity to load changes, simpler and safer control and operations [3]. Regarding the working parameters, they are different from other ORC applications: in particular, the maximum cycle temperature could be close to flame temperature, compatibly with the chemical stability of the working fluid, allowing also higher condensation temperature and a higher quality of the cogenerated heat, without excessive penalizations in the power cycle efficiency [30]. From an economic point of view Dong [29] underlined that small scale biomass ORC systems for domestic installation are still under development and not convenient due to high investment cost and long payback periods compared to medium size plants.

3.5 Energy Recovery from internal combustion engines (ICE)

Internal combustion engines are characterized by efficiencies closer to 50% in the cases of very big installations, this efficiency is associated to the amount of waste heat involved in the engine operations. The recovery of the thermal energy both from the exhaust gases and cooling circuit to produce useful mechanical work is of growing interest. Amongst other technologies such as: thermo-electricity and absorption cycle air conditioning, ORCs appear to be the most prominent solution for such applications as reported in the study by [31] showing how coupling of an ICE with an ORC for heat recovery could improve the overall net power and hence cycle efficiency. Zhang *et al*[32] presented thermodynamic analyses on bottoming ORC with an ICE for different system architectures. Considering only the design conditions, the authors concluded that the regenerated cycle was preferable as bottoming cycle for the studied engines.

Table 2 Small scale ORC manufacturers' website [33]

| Website | Expander | Size [kW] | Website | Expander | Size [kW] |
|-------------------------|----------------|-----------|------------------------|----------------------|-----------|
| www.electratherm.com | Screw | 50 | www.e-rational.net | Screw | 50-100 |
| www.barber-nichols.com | Turbine | 15-100 | www.eneftech.com | Scroll | 5-30 |
| www.gmk.info | Turbine | 50-100 | www.koehler-ziegler.de | Screw | 50-100 |
| www.freepower.co.uk | Turbine | 60-100 | www.enerbasque.com | n/a | 20-100 |
| www.durr-cyplan.com | Turbogenerator | 70 | www.termocycle.com | Turbine | 50-100 |
| www.ener-g-rotors.com | Gear | 40-60 | www.entrans.se | n/a | 50-100 |
| www.transpacenergy.com | Turbine | 100 | www.enogia.com | Turboexpander | 5-100 |
| www.infinityturbine.com | Screw | 10-100 | www.verdicorp.com | Turbocorp compressor | 20-100 |
| www.aqylon.com | Turbine | 100 | www.g-tet.com | Turbo-alternator | 25-100 |

4. Conclusions

In this paper, working fluid selection criteria, heat source type and field of application for ORC systems has been presented. Indications have been provided for the degree of maturity for different ORC technologies as in table 1, for systems within 100kW plant sizes. Literature suggests the use of positive

displacement type machines like the scroll as the expansion device for very small (<10kWe) applications while the screw and vane types expanders for very small-medium size (10-100kW) ORC applications. Furthermore, no single fluid has been identified as optimal for ORC as the choice depends on the specific application and the working conditions. A simulation model has been developed computing 6 different working fluids; the results obtained with the code show a good match between simulated and experimental results for R245fa, thus the code can be used for future studies on ORC system parameter analyses and different working fluids comparison. To conclude this review a list of manufacturers' website has been provided in table 2, while table 3 provides indications related to: plant size, working fluid type, heat source type, expander type, system thermal efficiency and system architecture for existing commercial installations as well as experimental prototypes.

Table 3 References installations for micro ORC

| Architecture | Expander | Application | Degree of Maturity | Working fluid | T _{cond} [°C] | T _{evap} [°C] | η_{exp} [%] | η_{th} [%] | Size [kW] |
|--------------|----------|--------------|--------------------|---------------|------------------------|------------------------|------------------|-----------------|-----------|
| SORC | Vane | Power | Mature | R11 | 20 | 99[34] | 30 | n/a | 1.4 |
| RORC | Turbine | Biomass CHP | Mature | Decane | 100 | 345 [35] | 70 | 86 | 0.76 |
| RORC | Turbine | Biomass CHP | Mature | Decane | 100 | 337 [36] | 70 | 86 | 5.02 |
| SORC | Scroll | WHR | V Promising | R123 | 10 | 180[37] | 70 | n/a | 1.98 |
| SORC | Scroll | WHR | V Promising | R245fa | 10 | 180 [37] | 70 | n/a | 2 |
| TORC | Piston | ICE-WHR | V Promising | Steam | 100 | 450 [38] | 78 | 44.9 | 24 |
| SORC | Vane | CHP | Mature | Steam | n/a | n/a [39] | 75 | n/a | 20 |
| SORC | Scroll | Solar | Developing | R245fa | n/a | 150 [40] | 70 | 75 | 3 |
| SORC | Scroll | Power | Mature | R245fa | n/a | 120 [41] | 70 | n/a | 1.5 |
| n/a | Screw | Solar | Developing | R245fa | n/a | 121 [42] | n/a | 80 | 50 |
| SORC | Scroll | WHR | V Promising | R245fa | 30 | 85 [9] | 70 | n/a | 1.7 |
| SORC | Scroll | CHP | Mature | R245 | 26.6 | 97.5 [43] | 75 | n/a | 2.1 |
| n/a | Vane | Solar | Developing | R11 | n/a | n/a [39] | 55 | n/a | 5 |
| SORC | Wankel | CHP | Mature | Steam | n/a | 170 [44] | 65 | n/a | 20 |
| SORC | Scroll | Power | Mature | R134a | n/a | 80 [45] | 65 | n/a | 1.5 |
| SORC | Scroll | n/a | n/a | Helium/R123 | n/a | 165 [46] | 68 | n/a | 1.82 |
| SORC | Scroll | Solar | Developing | R123/R134a | n/a | 150 [28] | 68 | 56 | 7.3 |
| n/a | Scroll | n/a | n/a | Ammonia | n/a | n/a [47] | 60 | 7.2 | 5 |
| n/a | Scroll | WHR | V Promising | Air | n/a | n/a [48] | 69 | n/a | 3.5 |
| RORC | Scroll | Power | Mature | R123 | 37 | 160 [49] | 49.9 | 92.3 | 0.3 |
| SORC | Scroll | Power | Mature | Steam | n/a | n/a [50] | 34 | n/a | 11.5 |
| SORC | Scroll | Solar | Developing | R113 | 35 | 136 [51] | 65 | 42 | 0.45 |
| SORC | Scroll | WHR | V Promising | R123 | n/a | n/a [52] | 83 | n/a | 2.96 |
| SORC | Gerotor | WHR | V Promising | R123 | n/a | n/a [52] | 85 | n/a | 2.07 |
| n/a | Scroll | n/a | n/a | R245fa | n/a | 100 [53] | 71.03 | 71.9 | 2.5 |
| n/a | Scroll | Power | Mature | R134a | n/a | n/a [54] | 77 | n/a | 1 |
| n/a | Scroll | Desalination | Promising | R134a | n/a | 60 [55] | 50 | 35 | 1 |
| SORC | Scroll | HVAC | Promising | R245fa | n/a | n/a [56] | 87.2 | n/a | 1 |
| SORC | Turbine | WHR | V Promising | R245fa | n/a | 137 [57] | n/a | 60 | 100 |
| RORC | Vane | CHP | Mature | HFE7000 | 46.2 | 123.[58] | 53.92 | 61.1 | 0.861 |
| n/a | Scroll | CHP | Mature | R245fa | 26.6 | 97.5 [43] | 75.7 | n/a | 2.1 |
| RORC | Turbine | Solar | Developing | R245fa | 30 | 137 [59] | 75 | n/a | 100 |

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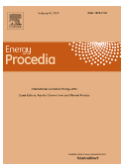
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Biography

John Besong OBI is holder of a B.Sc as well as an M.Sc in Mechanical Engineering at the university of Trieste where he is currently doing a PhD in distributed and micro-generation systems (ORC for Waste heat recovery systems) with some previous industrial experience in the HVAC field.