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## Innovative Organic Rankine arrangements for Water Savings in Waste Heat Recovery Applications

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### Abstract

Water is a natural resource of vital importance in the Singaporean context because of its high cost and scarcity. Indeed, 430mil gallons a day are consumed by the Singapore end-users, 45% domestic and 55% industry, with the latter expected to increase in the years to come by more than 60%. A significant amount of water is used for cooling towers which, in a hot and humid environment like that of the South-East Asian countries, have to operate extremely hard to reject heat from waste heat sources. While economics often limits the feasibility of low temperature Waste Heat Recovery (WHR) (40°C – 200°C), the large amount of waste heat available represents a huge opportunity for energy savings; indeed, the gaps remain such as maximise energy output, cooling loop in the condenser, smaller and compact size waste heat recovery systems, stabilising waste heat source and quality of waste heat. One valid alternative to reduce the cooling load in cooling towers (i.e. less water consumption) is represented by Organic Rankine Cycles (ORCs), which are mainly used to maximize the electricity output from a waste heat source. The operating principle of ORCs is the same as that of steam power plants and the main advantages of ORCs are simple and compact system structure and widely used heat sources and availability in recovering low temperature heat energy. In small scale, ORCs have not been commercialised due to techno-economic factors (i.e. low efficiency and payback period) and therefore there is a significant drive to find suitable solutions for electric power output between 10kWe and 100kWe. The paper deals with the development of key enabling components for small ORCs systems aimed to minimize water consumption from cooling towers by means of innovative ORC plant arrangements based on Turbo-Expander (TE) pumping system and internal regeneration processes. By means of this novel arrangement, improvement in global ORC performance are observed, reducing at the same time the cooling load at the condenser. The plant arrangement is described into details and results for different low temperatures WHR are presented, highlighting the benefit in terms of m<sup>3</sup> of saved water when Toluene and R245FA Working Fluid (WF) are adopted.

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## Nomenclature

CHP	Combined Heat and Power
ORC	Organic Rankine Cycle
RHE	Regenerative Heat Exchanger
TE	Turbo-Expander
WF	Working Fluid
WHR	Waste Heat Recovery

## 1. Introduction

Equatorial and sub-tropical areas such as Singapore will gain a significant benefit by the adoption of technologies that improve both primary energy and water savings. In countries where water is scarce, Organic Rankine Cycle (ORC) configurations which maximize the water savings should be preferred, whereas in other countries, where water availability might not be a pressing issue, ORC systems should be designed to maximize higher primary energy savings. Indeed, water is a natural resource of vital importance in Singapore because of its high cost and scarcity. Singapore end-users consume 430mil gallons a day, 45% domestic and 55% industry, with the latter is expected to increase in the years to come by more than 60% [01]. In the Singaporean context, due to the specific hot and humid environment, a significant amount of water is used for cooling towers which have to operate extremely hard to reject heat from waste heat sources. While economics often limits the feasibility of low temperature WHR (40°C – 250°C), the large amount of waste heat available represents a huge opportunity for energy savings and at the same time the capability of systems for reducing the cooling load in the rejection sink is a must. Accordingly, one valid alternative to reduce the cooling load in cooling towers (i.e. less water consumption) is represented by ORCs, which are mainly used to maximize the electricity output from a waste heat source. Figure 1 shows schematically how ORCs help in water saving and electricity generation in the WHR applications.

The operating principle of ORCs is the same as that of steam power plants and the main advantages of ORCs are simple and compact system structure, widely used heat sources and availability in recovering low temperature heat energy. In small scale, ORCs have not been commercialised due to techno-economic factors (i.e. low efficiency and payback period) and therefore there is a significant drive to find suitable solutions for electric power output between 10kWe and 100kWe. Indeed, ORC systems have not been widely commercialised for power outputs below a few hundred kilowatts [02, 03]. It has been argued that low temperature ORC systems below 10kWe are too inefficient to be economical due to low Carnot efficiencies [04]. Compared to higher power units these systems have low load factors but are justified by a large potential market.

Therefore, their successful uptake could be realised through the high-volume production of small-capacity, modular systems. The key scientific challenges are to develop tools to accurately predict expander and heat transfer devices performance, investigate the effects of working fluid replacement [05, 06] and then exploit an improved understanding of loss mechanisms to explore new plant arrangement and design methods to improve the performance envelope. Moreover, off-design models will benefit CHP and waste heat recovery applications since CHP applications require the matching of the heat and electricity supply with demand, often requiring the ORC components to operate at off-design conditions. Understanding off-design performance is critical to devising suitable control strategies. However, despite attempts to classify system configuration [07], and expander selection [08], according to the heat source, there remains a lack of thorough and balanced comparisons. The paper deals with the development of key enabling components for small ORCs systems aimed to minimize water consumption from cooling towers by means of innovative ORC plant arrangements based on turbo-pumping system and internal regeneration processes.

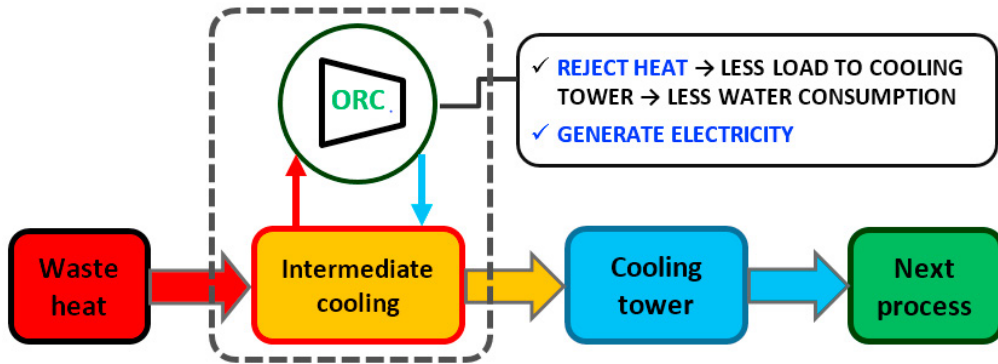


Figure 1: ORC Water Saving in Waste Heat Application

By exploring these solutions, the paper demonstrates the goal of design and develop technologies capable of exploiting the energy from low grade waste heat sources (e.g. hot water, flue gas from industrial processes/power plants) by producing low-carbon electric power and by reducing water consumption from cooling towers. Indeed, the paper demonstrates that this novel arrangement brings to improvement in global ORC performance, reducing at the same time the cooling load at the condenser. The plant arrangement is described in details and results for different WHR low temperatures are presented, highlighting the benefit in terms of  $\text{m}^3$  of saved water and of avoided cost when Toluene and R245FA Working Fluid (WF) are adopted for WHR temperatures of about  $250^\circ\text{C}$  and  $150^\circ\text{C}$ , respectively.

## 2. Proposed Arrangement

Different plant sections could help in the improvement of the whole plant efficiency and of the cooling load reduction at the condenser. For a given power, the higher the efficiency, the lower the water consumption for the condensing cold loop. The improvement in whole ORC performance can be achieved by reducing: the losses in the heat transfer devices; the parasitic losses in the pumping system; and increasing the capability of the expander to produce electricity. Moreover, innovative concepts of internal regeneration processes influence both the overall ORC efficiency and the reduction in the cooling load to be rejected in the cold sink (reducing the water media requirements), taking this second aspect a larger benefit from the bleedings concept. Taking as reference simple ORC plant layout into consideration [09], in figure 2 the proposed innovative ORC plant layout is shown.

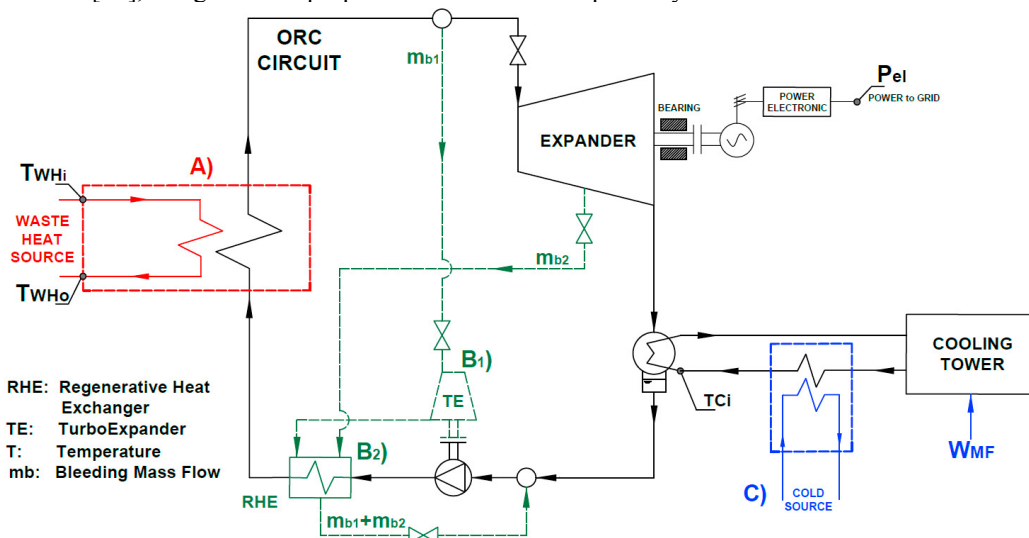


Figure 2: ORC Proposed Arrangement

In figure 2 the various possible options for traditional ORC power plant performance improvement and water savings have been depicted. A letter describes each option. Option **A** is related to enhanced heat exchanger performance, Option **D** takes the expander performance improvement into account, while Option **C** is representing the possibility of cooling the water loop if some cold energy source is available (e.g. LNG regasification or liquefied air tank). In this paper, analysis have been carried out for options **B1** and **B2** being related to the novelty of the plant arrangement. Benefits of the Options (**A**, **D**) have been embedded into the analysis by assuming components efficiencies and effectiveness of the best available technologies from the most updated state of the art. Solution **B1** and **B2** are related to the novelty of the plant layout. Indeed, **B1** and **B2** configurations take the bleeding of some working fluid mass flow rate before entering the expander ( $m_{b1}$  stream) and during the expansion, before the condenser ( $m_{b2}$  stream), respectively.  $m_{b1}$  mass flow rate is expanded into a small Turbo Expander (**TE**) - derivate from the car turbocharger, cheap and highly reliable and available, technology - for driving the main extraction pump and thus saving the huge pumping power consumption [10] and cost. Moreover, it has been proven that pumps for similar applications [10] have been operated at a shaft speed higher than 40,000 rpm. Such a rotational speed is comparable with that of the expander wheels of turbochargers. It means that with a dedicated design, it would be possible to directly drive the pump with the expander and the plant complexity (and related costs) is reduced because the adoption of an inverter, of a DC/AC controller components and of an electric motor for driving the pump is avoided. Indeed, in the **B1** configuration the valve - controlling the bleeding of the  $m_{b1}$  - is one of the parameters allowing for managing part load operations. After the expansion through the turbo-expander, the  $m_{b1}$  mass flow rate is condensed in a Regenerative Heat Exchanger (**RHE**), used for heating up the working fluid just pumped after the condenser. In addition to the pump driving  $m_{b1}$ , the adoption of a second bleed **B2** is taken into consideration. In the **B2** configuration, the  $m_{b2}$  is bled at a certain pressure level during the expansion and it is sent to the regenerator for recuperating the enthalpy content still available in the WF. The two options **B1** and **B2** are possible because ORC WF are dry fluids. It means that at the end of the expansion process, the thermodynamic state of the WF is still vapour. In case of a given net power to be delivery by the main ORC expander, these regenerative processes allow to reduce the primary energy low temperature heat sources to reduce the water consumption in the cooling loop and leading to a cost saving. Indeed, both  $m_{b1}$  and  $m_{b2}$  are not directed to the cold sink (the condenser), thus reducing the condensing load. As a consequence, these will affect also the design step for the heat rejection loop, reducing the sizes of the components (e.g. pipe length, circulating pump) and related capital costs. These solutions lower the operational costs as well. According to the above, in the next paragraph, the description of the modelling and of the simulation approach is presented and discussed.

### 3. Modelling and Simulating Approach

Low temperature WHR ORC plant arrangement calculations have been performed by means of the commercial software Aspen Plus®. The WF thermodynamic properties have been taken from the Aspen Plus® libraries and for the proposed solution WF have been modelled by adopting the PENG-ROBINSON correlations.

The model focuses on a control volume including only the working fluid circuit. The input to the system is a given waste heat power input, the evaporation temperature and the condensing temperature. The model adjusts the mass flow of the working fluid according to the waste heat power and to the related generated electric power output in order to achieve saturated steam at the outlet of the evaporator since no-super heating is needed for dry fluids. In the innovative arrangement, the model adjust the bleeding fraction before the main expander so that the mass flow in the turbo-expander delivers the work required by the pump.

### 4. Test Case and Results

In order to understand the practical benefits in terms of water savings and related cost savings of the proposed arrangement, various investigations have been performed. According to the wide range of the low temperature waste heat availability, evaluations have been carried out assuming an evaporator temperature ranging from 120°C to 250°C, with a 10°C incremental steps. Mainly two sizes of the ORC plant have been taken into consideration by assuming two values of the waste heat power available for the cycle, 300kW (Case #1) and 500kW (Case #2). Furthermore,

parametric investigations have been performed by assuming three different condenser temperature, 33.0°C, 35.0°C and 38°C. Pinch point at the RHE has been assumed to be 5°C.

The above mentioned assumptions, given in table 1, have led to select the most suitable WFs for such a low temperature WHR applications. For temperature of around 150°C and 250°C, R245FA and Toluene have been selected by the optimization procedure as the best fitting WFs, respectively.

Being this solution addressed to water saving, the net electric power generated in the innovative arrangement is constrained to assume the same value of traditional ORC power plant. The increase on the specific work results indeed in the reduction of the WF mass flow operated by the ORC plant, being the waste heat power input given. Indeed, under these conditions, the higher the ORC whole efficiency, the lower the mass flow rate required for generating electricity. Consequently, also the cooling load at the condenser is reduced. Figure 3 shows the results of these preliminary evaluations for the innovative arrangement shown in figure 2 in comparison with the typical ORC [09] arrangement are summarized in figure 3. Ranging from 40kWe up to 120kWe, yearly water saving rises from 9% up to 24% bringing to about 40kSGD and 140kSGD cost saving, assuming the typical Singaporean price for water of around 1.2SGD/m<sup>3</sup>. These saving correspond to 30,000m<sup>3</sup> and 114,000m<sup>3</sup> mass water saving over a year.

Table 1. List of the assumptions for the evaluations

Quantity	Value	Measurement Unit
Working Fluid	Toluene/R245FA	[-]
WHR Low Temperature	[120.0; 250.0]	[°C]
Waste Heat Power Input	300.0/500.0	[kW]
Expander and Pump Isentropic Efficiency	0.8	[-]
RHE Pinch Point	5.0	[°C]
Pressure Loss	0.0	[kPa]
Condensing Temperature	33.0/35.0/38.0	[°C]

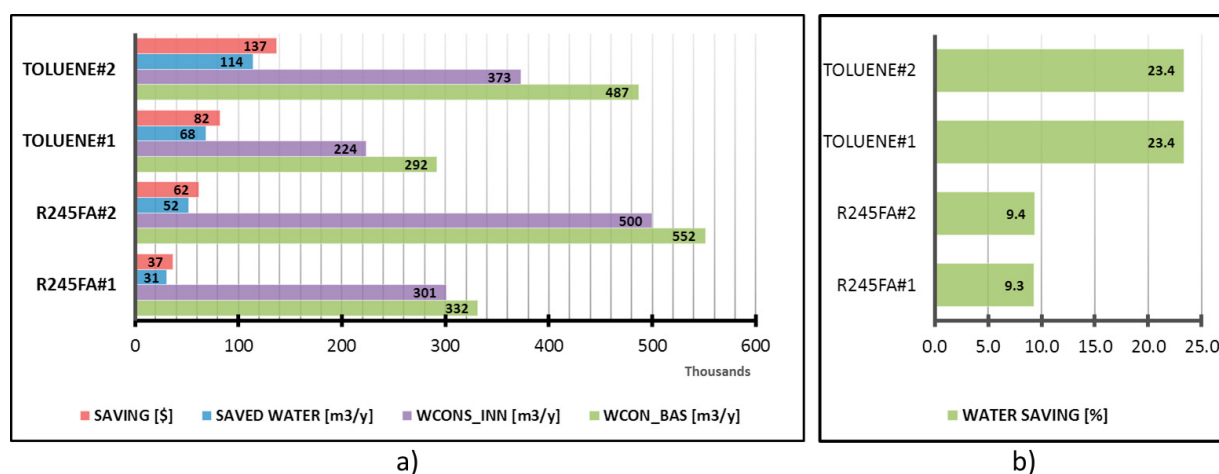


Figure 3: Preliminary Results in Water and Cost Saving with the Adoption of the Innovative ORC Layout

## 5. Conclusions

The paper deals with an innovative ORC plant arrangement in the low temperature WHR context, where the savings of water is a necessity. Indeed, the huge amount of low grade heat which is not being recovered will deeply impact on cooling systems such as cooling towers bringing to very significant water savings with respect of the traditional heat recovery plants. The paper has demonstrated that operating minor modifications on a traditional ORC

plant arrangement it is possible to design and develop a technology capable to exploit the energy from low grade waste heat sources (e.g. hot water, flue gas from industrial processes/power plants) thus producing low-carbon electric power and reducing water consumption from cooling towers. In respect of the boundary conditions and of the low temperature WHR availability, the reduction (saving) in water consumption ranges between 9% and 23% if compared with the simple ORC configuration. These cost savings correspond to about 40kSGD and 140kSGD respectively.

Looking also at highly integrated industrial estates providing also for district cooling operation, depending on the availability of cold energy source (e.g. LNG regasification and Liquid Air Tank), the exploitation of the option C should result in a higher water and costs savings. This configuration could significantly bring to reduce the payback period of WHR ORC technologies, potentially making the retrofitting solution an interesting solution.

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