

A Review on Combining Micro Gas Turbines with Organic Rankine Cycles

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Abstract. Current energy conversion machines such as the micro gas turbine can be improved by harvesting the low-grade energy of the exhaust. A prominent option for such is the organic Rankine cycle due to its relatively efficient and reliable design. This manuscript presents a review on the subject and is the first step toward the design of an organic Rankine cycle bottoming a 100 kWe recuperated gas turbine. After introducing and covering the historical development of the technology, appropriate guidelines for defining the cycle arrangement and selecting the fluid are presented. At last, the viability of the cycle is assessed by assuming an appropriate efficiency value and general cost functions. The organic Rankine is expected to generate an additional 16.6 kWe of power, increasing the electrical efficiency from 30 to 35%. However, the capital cost increase was estimated in 48%.

1 Introduction

The ever-growing amount of resources required to sustain anthropogenic activity is an increasing concern worldwide. The dependency on finite-nature fossil fuels exposes the unsustainability of the current energy market. Moreover, the combustion of fossil fuels introduces to the atmosphere substances that were previously trapped beneath the ground, which harm the environment. Governments address these issues by enforcing legislation that promote the harvesting of renewable energy sources and the reduction of fuel consumption, which embolden the development of novel energy conversion methods and the improvement of current ones.

The development of technologies to exploit low and medium heat sources is increasing due to the stimulus toward higher efficiencies when converting resources into energy [1]. On one front, energy sources such as geothermal provide renewable energy at low temperature. On the other, prime movers and industrial processes waste a significant amount of energy that could be availed. For instance, considering cement, steel, and glass industries plus gas compressor stations in Europe, Campana et al. [2] estimates the potential of recovering 2.7 GW of gross power. Harvesting heat that would otherwise be wasted also

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contributes towards the reduction of greenhouse gas emissions [3].

Thermodynamic cycles are designed to achieve a high efficiency within the boundaries imposed by each application. Some prominent options for the conversion of low-grade heat into power are the Kalina, trilateral flash, and organic Rankine cycles. According to Bao and Zhao [4], unlike the Kalina and trilateral flash cycles, which present a complex structure and a difficult two-phase expansion, respectively, the organic Rankine cycle (ORC) is being widely accepted due to simple structure, easy maintenance, and high reliability. The Kalina cycle is expected to achieve a higher efficiency than the ORC [5], which highlights the fact that a simpler cycle can be more viable due to a higher availability and a lower cost of acquisition and maintenance.

The organic and steam Rankine cycles are quite similar, presenting the same four processes: (1), heat addition in the evaporator; (2), work extraction in the turbine; (3), heat extraction in the condenser; and (4), work addition in the pump (Fig. 1). The major difference between both cycles is the working fluid employed, since organic fluids present a significantly lower latent heat than water, which allows the evaporation of a larger mass flow with the same heat, reducing the relative losses due to gaps within the expander [6]. Furthermore, several organic fluids present a positive slope of the saturated vapor curve, thus, a dry expansion process that is more appropriate for low-grade heat since superheating is not required [1]. Hung, Shai, and Wang [7] suggest a threshold of 370 °C below which the steam Rankine cycle becomes poorly efficient.

The ORC has gained popularity in the last two decades due to its potential of harvesting a wide range of energy sources [8]. For instance, reciprocating engines, micro gas turbines, and industrial processes discharge heat in the range of 300 – 450 °C, 250 – 350 °C, 200 – 500 °C, respectively, which can be harvested by an ORC [9]. Although some heat sources are above the aforementioned threshold, ORCs are better suited than steam Rankine cycles for distributed power generation and mobile applications due to minimum on-site control and smaller footprint [10]. Moreover, considering the limitations in plant capacity imposed by the cost of gathering biomass, ORCs provide cost-effective solutions for decentralized small-scale power generation [11].

When comparing micro gas turbines with reciprocating engine for small-scale power generation, the former presents lower emissions although achieving a lower efficiency [12]. Considering that the combination of gas turbines with steam Rankine cycles has proven to yield unmatched thermal efficiency at the higher-range of energy production [13], the combination of micro gas turbines with ORCs appropriately designed to avail the low-grade heat of the exhaust shows great potential, especially when considering that gas turbines with smaller power levels benefited the most when combined with ORCs [14].

Even though research on ORC with evaporation temperature in the range of a micro gas turbine exhaust is quite limited, developments on the effective combination of these thermodynamic cycles is expected to increase [4]. This manuscript offers a review on the subject, arising as a first step toward developing an ORC compatible with a 100 kW_e recuperated gas turbine, composed by a radial compressor rotating at 70,000 rpm with a pressure ratio of 4.5, a lean pre-mix combustion chamber with an outlet temperature of 950 °C, and a radial turbine with an outlet temperature of 650 °C. The micro gas turbine burns natural gas with an electrical efficiency of 30% and provides an exhaust mass flow of 0.8 kg/s at 270 °C.

2 Organic Rankine Cycle Development

The concept of employing organic substances as working fluid dates back centuries, with the first patent emitted for an engine using ether in 1826; however, the modern ORC with the same principles as employed today is attributed to Professor D'Amelio of the

University of Naples that described a solar plant for irrigation using monochloroethane as working fluid in 1936 [11]. The ORC development halted in the 1980s due to high interest rates and cheap fossil fuels, shutting down most experiments since the technology was no longer economically attractive [15]. From there on, the development of ORC projects slightly increased until the 21st century when the technology showed remarkable growth, accounting for 2 GWe of worldwide installed capacity in 2017 [16].

Considering the development of ORCs according to heat source, solar energy is incipient, biomass and geothermal are already mature, and waste heat recovery is expected to show the fastest growth [17]. Considering gas turbines, waste heat recuperation by ORC becomes attractive for smaller-sized and recuperated cycles due to a lower exhaust temperature. By harvesting the heat through ORCs, Bianchi et al. [18] estimates that the power production of gas compressions stations can increase by roughly 35% and Chacartegui et al. [19] estimates that gas turbines which generate as low as 5 MWe can achieve an efficiency in excess of 50%. For micro gas turbines, on the other hand, the limited heat available indicates that a low ORC efficiency is expected since it is strongly correlated with the power output [23]. Thus, achieving a viable performance to justify the additional cost of the bottoming ORC becomes a challenge.

3 Cycle Arrangement

Although achieving a relatively low efficiency, ORCs are designed to harvest low-cost heat sources such as geothermal and waste heat, which legitimates the increasing number of emerging companies devoted to this technology [17]. At the same time, the commercially available units differ significantly from each other at system and component level due to the wide range of applications covered by ORCs [11]. Thus, considering the limited efficiency and the case-by-case design, the first step towards designing the proposed ORC is the proper definition of the cycle arrangement.

3.1 Intermediate Heating Medium

Thermodynamic cycles can receive heat directly or indirectly through an intermediate heating medium such as thermal oil. The intermediate heating circuit receives heat from the source and transfer it to the ORC, providing greater stability during load change, energy storage potential, and simpler control over the cycle output [10]. Thus, an intermediate heating circuit is highly recommended for discontinuous heat sources [2]. However, the complexity, cost, weight, and size of the cycle increases and the maximum temperature reduces due to limited heat transfer between both ends of the circuit, negatively affecting the efficiency of the cycle [1].

Considering that the micro gas turbine is expected to operate stably and that complexity, cost, weight, and size are critical issues, along with achieving a viable efficiency, an intermediate heating medium is not recommended for the present case. However, special attention must be paid to avoid the presence of hot spots that could promote the decomposition of the working fluid [11].

3.2 Superheating

Steam Rankine cycles usually employ superheating for two reasons: (1), expanding from saturation would lead to an unacceptable moisture at the end of the process due to the negative slope of the saturated curve; and (2), a higher efficiency is attainable. Since

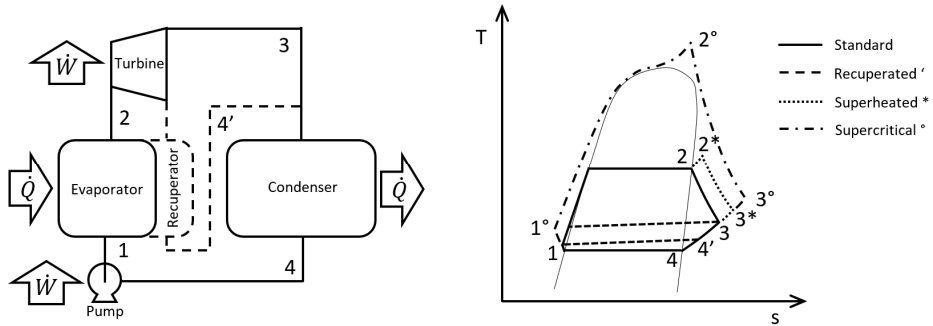


Fig 1. Schematic representation of the different ORCs.

organic fluids usually present a positive saturation slope, moisture after expansion is not an issue. Regarding the efficiency, Chen, Goswami, and Stefanakos [5] states that due to the isobaric curve's divergence with superheating, the efficiency is reduced since the additional heat required is not compensated by the additional work generated, while Astolfi [20] arguments that superheating is recommended when the fluid critical temperature is lower than the heat source maximum temperature since the average temperature difference is reduced without limiting the heat source exploitation.

Due to a lack of consensus, the employment of superheating must be investigated in simulations; however, it is worth noting that a slight degree of superheating is useful to prevent liquid particles entering the expander, which can promote blade erosion in turboexpanders [1].

3.3 Transcritical

The main advantages of transcritical cycles are the reduction of the heat transfer irreversibility due to smaller temperature differences in the vapor generator and the downsizing of the high-pressure cycle components that operate with a higher-density fluid [6]. On the other hand, the main disadvantages are difficulties in operation, more expensive heat exchangers, and higher backwork ratio, which is defined as the pump consumption divided by the work output [5].

When comparing organic and steam Rankine cycles, the former presents a higher mass flow of working fluid due to a lower latent heat, which increases the backwork ratio. For this reason, the pump irreversibility can substantially decrease the ORC efficiency [21]. The backwork ratio becomes even more pronounced as the power scale reduces as shown by Landelle et al. [22], which estimates a backwork ratio growth from 5% at a 100 kW scale to 30% at a 1 kW scale.

For the present case, although the cycle footprint would be reduced by operating above critical pressure, the availability could be compromised by difficulties in operation and the overall cost of acquisition and maintenance would increase. Furthermore, at smaller power scales, the high backwork ratio could overturn the lower irreversibility in the vapor generator. For these reasons, operation above critical pressure is not recommended. It is worth noting that most operational cycles in literature are subcritical since the average between working fluid pressure and fluid critical pressure was found to be 0.4 [22].

3.4 Recuperator

The expansion of dry working fluids leads to a superheated state; therefore, another heat exchanger could be added to recuperate some heat back to the cycle before

condensation. Considering that the heat added to the cycle is the same, the recuperated heat enables a larger mass flow to pass through the vapor generator, although imposing a restriction at the end of the expander that reduces the specific work attainable. By adding a recuperator to the cycle, Maraver et al. [23] concludes that the cycle thermodynamic performance will improve for most applications in which the heat source minimum temperature is limited by technical constraints while Zhang et al. [24] concludes that recuperation is recommended for high temperature heat sources.

Considering the acid dew point limitation on the heat source temperature reduction and the relatively high exhaust temperature of the micro gas turbine, the addition of a recuperator is expected to increase the thermodynamic performance of the present case. Although the thermodynamic benefit can be quite limited [11], adding a recuperator also avoids excessive cooling of the heat source [12] and reduces the condenser heat load, which contributes toward reducing component size [25]. Thus, the recuperator is recommended for the present case.

4 Working Fluid

Considering the wide range of organic substances available and their significantly different thermodynamic properties, the selection of an appropriate fluid for ORCs becomes a crucial step in designing the cycle. The fluids can be divided into three categories according to the slope of the saturation curve: simpler molecules have a negative slope and are called *wet* since an expansion process from saturation will result in the formation of moisture, as the complexity increases and the heat capacity ratio decreases, the slope becomes positive and the fluids are conversely called *dry*, and between both with zero slope are the *isentropic* fluids [12].

Besides the saturation curve slope, other properties have an impact on the cycle design. For instance, a higher molecular weight reduces the expander enthalpy drop and, consequently, its dimension, although supersonic flow can become an issue [4], while a higher critical temperature indicates a higher volume flow ratio that could reduce the expander efficiency [26]. According to Maraver et al. [24], the lack of an ideal working fluid implicates that its selection must be integrated into the design process. For instance, fluids with higher molecular weight such as siloxanes could have a significant impact in reducing heat exchanger size and cost [27]. Moreover, other features such as chemical and thermal stability, environmental impact, and safety issues must also be addressed [28]. A compromise between these aspects is required to select the most appropriate fluid. The purpose of this revision is to narrow down the selection process.

Considering the maximum temperature of the waste heat of 270 °C and the minimum temperature constrain, Maraver et al. [24] concludes that pentane is the optimum fluid within the 300 to 120 °C temperature boundary and White et al. [29] indicates that pentane achieves the lowest specific investment cost for a maximum temperature of 250 °C. However, Invernizzi, Iora, and Silva [12] state that although pentane obtained the best thermodynamic performance when designing a bottoming ORC for a 100 kWe micro turbine, the hexamethyldisiloxane (MM) expander size parameter is more suitable. Thus, the selection process must screen a wide variety of fluids, ranging from light alkanes to heavy siloxanes.

5 Viability

Micro gas turbines offer several advantages such as compact size, fuel flexibility, low emission, and high reliability; however, their relatively low efficiency and high cost hinder

the wide implementation of this technology [30]. The combination of the micro gas turbine with a bottoming ORC could improve its competitiveness by increasing the overall efficiency, yet the thermal efficiency of the ORC is strongly related to the power scale [23], thus, achieving a viable performance that justifies the additional cost is a challenge due to the small scale of the waste heat available.

Regarding the development of recuperated ORCs bottoming 100 kWe gas turbines, Invernizzi, Iora, and Silva [12] states that an additional 45 kWe can be generated, increasing the efficiency from 30 to 40%, while Caresana et al. [31] obtains 25 kWe of additional power, which increases the efficiency from 30 to 37.5%. However, when compared to the present case, the waste heat mass flow and temperature are respectively 25% and 11% higher in the former study and the condenser is cooled by an open water circuit in the latter. Therefore, this manuscript presents more conservative figures. Considering a waste heat temperature between 270 and 70 °C, resulting in an available heat of approximately 166 kW, and an electric efficiency of 10%, which was estimated from an experimental database [23], the ORC is expected to generate around 16.6 kWe, increasing the overall efficiency from 30 to 35%.

The viability of coupling a micro gas turbine with an ORC will depend on achieving better economic indicators [32]. Several authors present cost functions to estimate the components prices in relation to heat exchanger areas and turbomachines power capacities [1,33]. However, these values were not established in this preliminary analysis. Thus, a more general relation was employed that establishes a value of 1.2 k€/kWe for the micro gas turbine and 2.5 k€/kWe for the ORC [12], which resulted in a 48% higher capital cost. This significant increase indicates that the combined cycle will only become more economically attractive if the utilization factor is high.

Ultimately, micro gas turbines compete with diesel engines in the small-scale power generation market, which are cheaper and achieve an efficiency around 40% [34]. Although achieving a lower efficiency, micro gas turbines are more reliable, emit less pollutants, and offer greater fuel flexibility [31]. Therefore, growing environmental and fuel-diversification concerns could favor the micro combined gas and organic Rankine cycle in the future.

6 Conclusion

A review on developing an ORC to harvest the waste heat from a 100 kWe recuperated gas turbine was presented. This preliminary assessment recommended a cycle arrangement that can be summarized as direct heating, slightly superheated, subcritical, and recuperated with an air-cooled condenser. Pentane was flagged as a prominent option of working fluid, although an appropriate screening process in which both thermodynamic and economic considerations are considered is required to define the optimal fluid.

The ORC is expected to generate an additional 16.6 kWe of power, increasing the power output from 100 to 116.6 kWe and the efficiency from 30 to 35%. However, the capital cost increase was estimated in 48%, which highlights that the combination of both cycles will only become economically attractive if the utilization factor is high. Although achieving a lower efficiency than diesel engines, growing environmental and fuel-diversification concerns could favor the selection of micro combined gas and organic Rankine cycles in the small-scale power generation market.

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