Organic Rankine Cycle (ORC) in Waste Heat Recovery Systems (WHRS) –A Literature Mini Review

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Organic Rankine Cycle (ORC) in Waste Heat Recovery Systems (WHRS) - A Literature Mini-Review

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Abstract: In the quest for sustainable and efficient energy use, Organic Rankine Cycle (ORC) is emerging as a promising solution within Waste Heat Recovery Systems (WHRS). This literature mini-review provides a brief overview of the current state of research in the application of ORC, shedding light on methodologies, challenges, and potential avenues of discovery. Approximately 55% of thermal power plant heat consists of wasted energy and offers a significant recovery potential. Using low-grade energy to generate high-level power, the integration of ORC into energy systems increases overall system efficiency and reduces thermal pollution. This review addresses fluid selection, highlighting Isobutane as an effective choice. The effect of different heat sources, including exhaust gases and combined sources, is being investigated. The article discusses the importance of thermodynamic cycle stages, system parameters and working fluid properties. Evaluation and optimization components are highlighted, including the impact on the power plant efficiency of a chemical/oil tanker. In particular, the study demonstrates the superior performance of Isobutane and highlights its potential for improved sustainability. Overall, this mini-review contributes to advances in sustainable energy use by providing valuable insight into ORC applications.It is aimed to shed light on various scientific studies, articles, congress and symposium papers that will be conducted in this field in the coming years.

Keywords:*Organic Rankine Cycle, Waste Heat Recovery Systems, Sustainability*

I. INTRODUCTION

In recent years, the quest for sustainable and efficient energy utilization has driven significant research and development in the field of Waste Heat Recovery Systems (WHRS). Among the various technologies employed to harness wasted thermal energy, the Organic Rankine Cycle (ORC) stands out as a promising and versatile solution. This literature mini-review aims to provide a concise yet comprehensive overview of the current state of research and advancements in the application of ORC within the realm of Waste Heat Recovery Systems. By delving into key studies and findings, this paper seeks to illuminate the diverse methodologies, challenges, and potential avenues for further exploration in this rapidly evolving intersection of organic Rankine cycles and waste heat recovery.

Waste heat from thermal power plants constitutes a very large portion of total heat input, approximately 55% of the total heat content of the fuel burnt. The potential for recovery is phenomenal, but wide spread commercial acceptance still requires research and development efforts. Waste heat recovery reduces thermal pollution and fosters energy conservation. Integrating an Organic Rankine Cycle (ORC) to the energy system, such as power plants, to utilize low-grade energy (flue gas) to generate high grade energy (power) eases the power burden and enhances the combined system efficiency [1]. The ORC differs from the conventional Rankine cycle because it can operate with a great variety of organic fluids and no with water/steam. Moreover, it can operate with various heat sources such as solar energy, geothermal energy,fuel energy (e.g., biomass or biogas), and waste heat. The lower critical temperature of the organic fluids makes possible the optimum exploitation of the aforementioned medium and low-grade energy sources, the critical factor for the viability of this technology [2]. An investigation into waste heat recovery in Organic Rankine Cycle (ORC) with dry fluids, including Benzene, Toluene, p-Xylene, R-113, R-123, revealed a dependency of irreversibility on the type of heat source. The results indicated that the highest efficiency was exhibited by p-Xylene, whereas Benzene demonstrated the lowest [1,3]. An exploration of the Organic Rankine Cycle (ORC) with fluids R-123 and Isobutene revealed a higher thermal efficiency with R-123 as opposed to Isobutene, as concluded in the respective study [1,4]. The presence of hydrogen bonds in certain molecules such as water, ammonia, and ethanol has been reported to lead to wet fluids, attributed to larger vaporization enthalpy, rendering them inappropriate for the ORC system [1,5]. The recovery of low-grade waste heat based on different slopes and shapes of the saturation vapor curves of fluids has been reviewed, and it has been concluded that isentropic fluids are most suitable for recovering low-temperature waste heat [1,6]. The performance and optimization of ORC for waste heat recovery using HFC-245fa (1,1,1,3,3-pentafluoropropane) as a working fluid driven by exhaust heat have been studied, and it has been pointed out that improving the system performance is achievable by maximizing the utilization of exhaust heat [1,7]. An analysis of ORC using dry fluids, namely R-113, R 245Ca, R-123, and isobutane, was presented, where the regenerative ORC was examined and compared with the basic ORC to determine the configuration that offers the best thermal efficiency with minimum irreversibility [1,8]. A review paper related to various approaches for generating power from industrial waste heat recovery, including chemical heat pumps, adsorption and absorption cycles for cooling and heating, ORC, supercritical Rankine cycle (SRC), and trilateral cycle, as well as thermal energy storage systems, was presented [2,9]. A review paper related to the ORC system coupled with different heat sources such as solar energy, geothermal energy, and industrial waste heat recovery systems was presented [2,10]

II. THERMODYNAMIC CYCLE

The basic components of an Organic Rankine Cycle (ORC) system, such as the heat recovery system (HRS), turbine, condenser and fluid pump, which are responsible for the heat transfer of waste heat in the organic fluid, can be summarized as follows (Fig I.). Heat Recovery System (HRS):It is a device responsible for the transfer of waste heat to organic fluid.Thermodynamic Cycle Stages: The cycle begins with a saturated fluid at low pressure (state point 1). The pump increases the pressure, turning the fluid into a high-pressure supercooled liquid (state point 2).HRS, its enthalpy increases and the fluid becomes a high-pressure saturated liquid in the economizer (state point 21).The evaporator turns the fluid into high-pressure saturated vapor (state point 22), and the superheater turns the vapor into high-pressure superheated vapor (state point 3).Then, expansion occurs in the turbine and work is produced. The turbine exit is in the form of low pressure superheated steam (state point 4) System Parameters: The minimum temperature difference in HRS is called the "pinch point" between the heat source and the organic fluid and is generally chosen in the range of 5-30 °K.For gas heat sources, it generally has higher values than for liquid heat sources [2].

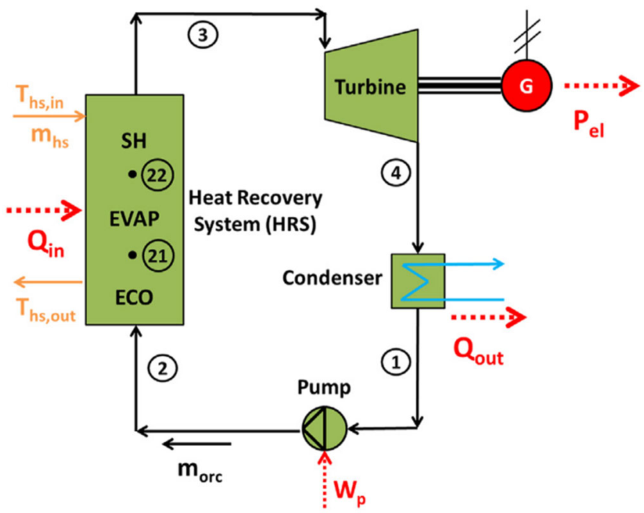

FIG I. ORGANIC RANKINE CYCLE WITH HEAT RECOVERY SYSTEM [2]

The energy supplied to the heat recovery system (Q_{in}) is defined through the energy balance within the working fluid volume:

$$Q_{in} = m_{orc}.(h_3 - h_2)$$

The determination of work output resulting from the turbine expansion (W_T) is computed as follows [2]:

$$W_T = m_{orc}.(h_3 - h_4)$$

Thermodynamic cycle depiction and illustration of the heat transfer phenomenon within the heat recovery system (T-h Diagram) can be found respectively in (Fig II. And Fig III.)

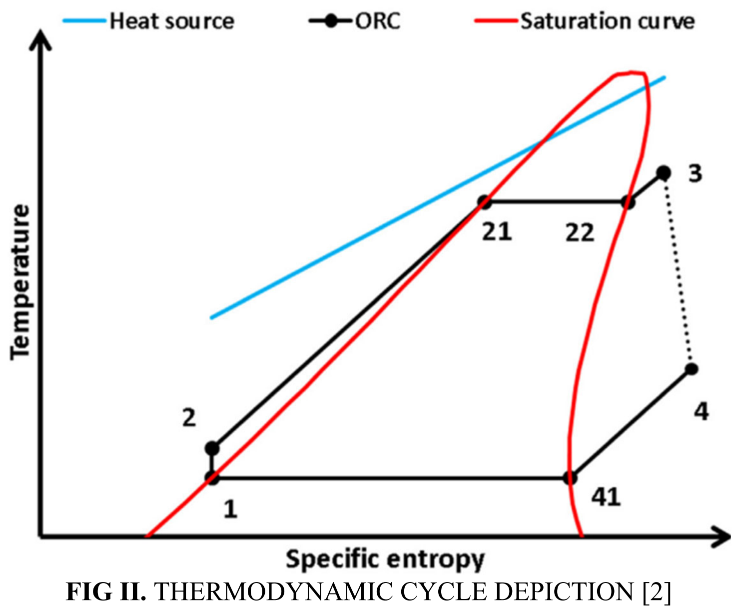

FIG II. THERMODYNAMIC CYCLE DEPICTION [2]

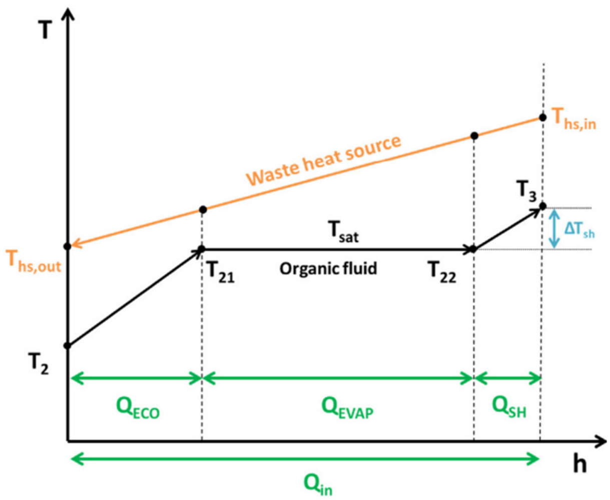

FIG III. ILLUSTRATION OF THE HEAT TRANSFER PHENOMENON WITHIN THE HEAT RECOVERY SYSTEM (T-H DIAGRAM) [2]

The determination of electricity generation in the generator (P_{el}) involves the utilization of the electromechanical efficiency (η_{mg}), typically around 95% in practical implementations:

$$P_{el} = \eta_{mg} \,.\, W_T$$

The turbine expansion is represented by incorporating the isentropic efficiency ($\eta_{is,T}$), characterized as follows:

$$\eta_{is,T} = \frac{h_3 - h_4}{h_3 - h_4, is}$$

Typically, the isentropic efficiency varies between 70% and 90%, depending on factors such as turbine design, working fluid, and pressure ratio. The computation of heat dissipation from the condenser to the surroundings (Q_{out}) is determined by the following calculation [2]:

$$Q_{out} = m_{orc} \cdot (h_4 - h_1)$$

The computation of pumping work consumption (W_p) is conducted using the provided formula. The motor efficiency (η_{motor}) typically falls within the range of 70% to 80%.

$$W_p = \frac{m_{orc} \cdot (h_2 - h_1)}{\eta_{motor}}$$

The net electrical output of the Organic Rankine Cycle ($P_{el,net}$) is determined by subtracting the electricity generated in the generator (P_{el}) from the work required by the pump (W_p):

$$P_{el,net} = P_{el} - W_p$$

The thermal efficiency of the Organic Rankine Cycle (η_{orc}) is established by the division of the net electricity production by the heat input in the Heat Recovery System (HRS):

$$\eta_{orc} = \frac{P_{el,net}}{Q_{in}}$$

The computation of the heat input in the Heat Recovery System involves applying the following equation. In the case of a gas working fluid, it is feasible to employ the mean specific heat capacity ($c_{p,hs}$) and incorporate temperature levels into the subsequent formula:

$$Q_{in} = m_{hs} . (h_{s,in} - h_{s,out}) \approx m_{hs} . c_{p,hs} . (T_{hs,in} - T_{hs,out})$$

In practical scenarios, the waste heat fluid departs from the Heat Recovery System with a temperature surpassing the reference temperature ($T_{hs,out} > T_0$), leading to less than 100% efficiency in harnessing the waste heat source. The reference temperature (T_0) is commonly designated at 298.15 °K (or 25°C), although, in certain instances, it may align with the ambient temperature.

The efficiency of the heat recovery system (η_{HRS}) holds significance, being characterized by the relationship between the actual heat input in the system (Q_{in}) and the maximum achievable heat input in the system ($Q_{in,max}$) [11].

$$\eta_{HRS} = \frac{Q_{in}}{Q_{in,max}} = \frac{m_{hr}.(h_{r,in} - h_{r,out})}{m_{hr}.(h_{r,in} - h_0)} \approx \frac{T_{hr,in} - T_{hr,out}}{T_{hr,in} - T_0}$$

The overall system efficiency (η_{sys}) is determined by the division of the net electricity production by the maximum attainable heat input in the system:

$$\eta_{sys} = \frac{P_{el,net}}{Q_{in,max}} = \eta_{orc}.\eta_{HRS}$$

The exergy efficiency of the system ($\eta_{ex,orc}$) can be expressed as follows:

$$\eta_{ex,orc} = \frac{P_{el,net}}{Ex_{HRS}}$$

The exergy flux associated with the heat input in the Heat Recovery System (Ex_{HRS}) can be formulated as:

$$Ex_{HRS} = m_{hs} . c_{p,hs} . (T_{hs,in} - T_{hs,out}) - m_{hs} . c_{p,hs} . T_0 . \ln[\frac{T_{hs,in}}{T_{hs,out}}]$$

In the aforementioned equation, it is essential for all temperature values to be in Kelvin units. A common choice for the reference temperature (T_0) is 298.15 °K. The exergy efficiency of the system ($\eta_{ex,sys}$) can be delineated under the assumption that optimal utilization occurs when the waste heat source exits the Heat Recovery System at the reference temperature. Typically, exergy efficiency is associated with maximizing work output, making this definition rational [2].

$$\eta_{ex,sys} = \frac{P_{el,net}}{Ex_{hs,inlet}}$$

The exergy flux related to the heat inlet ($Ex_{hs,inlet}$) is specified as [2]:

$$Ex_{hs,inlet} = m_{hs} . c_{p,hs} . (T_{hs,in} - T_0) - m_{hs} . c_{p,hs} . T_0 . \ln[\frac{T_{hs,in}}{T_0}]$$

III. WORKING FLUIDS

The waste heat can be recovered by means of two different setups: (1) direct heat exchange between the waste heat source and the working fluid and (2) a heat transfer fluid loop is integrated to transfer the heat from the waste heat site to the evaporator.The general table of working fluids, compiled from various previous studies in the literature, is given in Table I. [12].

TABLE I. SUMMARY OF DIFFERENT WORKING FLUIDS STUDIES [12]

Author(s)	Application	Cond. Temp.	Evap. Temp.	Recommended fluid(s)
Badr,1985 [13]	WHR	30 - 50°C	120°C	R113
Liu et al., 2004 [5]	Waste Heat Recovery	30°C	150-200°C	Benzene,Toluene, R123
Lemort et al.,2007 [14]	Waste Heat Recovery	35°C	60-100°C	R123,n-pentane
Mago,2008 [8]	WHR	25°C	100-210°C	R113
Dai,2009 [15]	WHR	25°C	145°C^{a}	R236EA
Desai,2009 [16]	WHR	40°C	120°C	Toluene,Benzene
Gu,2009 [17]	WHR	50°C	80-220°C	R113,R123

a : Max / min temperature of the heat source /sink instead of evaporating or condensing temperature

From numerous studies related to the selection of fluids for Organic Rankine Cycle (ORC) Waste Heat Recovery (WHR) systems (Table 1), certain characteristics of working fluids can be outlined: High-Temperature Applications (Close to 300°C): Fluids with high critical temperatures or boiling points, such as toluene and silicone oils, are commonly employed. Moderate and Low Temperatures (Typically Below 200°C): Hydrocarbons like pentanes or butanes and refrigerants such as R227ea, R123, R245fa, and HFE7000 are considered suitable candidates.Vapor Density: Fluids with high vapor density are recommended as they permit the reduction of turbine size and heat exchanger areas. Additional Working Fluid Characteristics: Flammability: Consideration of the flammability of the chosen fluid is crucial.Toxicity: Assessing the toxicity of the working fluid is important for safety. Environmental Impact: Evaluate the environmental impact of the fluid in terms of sustainability. Cost: Factor in the cost of the working fluid for economic feasibility. Chemical Stability: Ensure the chemical stability of the fluid, and operate cycles well below the maximum thermal stability temperature [12]. While R123, n-pentane, Toluene, and Benzene exhibit more flammable characteristics, Benzene and Toluene, in particular, are also more toxic. Therefore, hydrocarbons like R113, R245fa, R236EA can be considered safer and more suitable alternatives.

IV. PERFORMANCE EVALUATION AND OPTIMIZATION

Many components exist in the ORC-WHR system. This section will briefly describe the modelling of following components: evaporator, pump, valves, junction before turbine, expander and reservoir. A complete overview of the ORC-WHR system modelling can be found in Fig IV.[18].

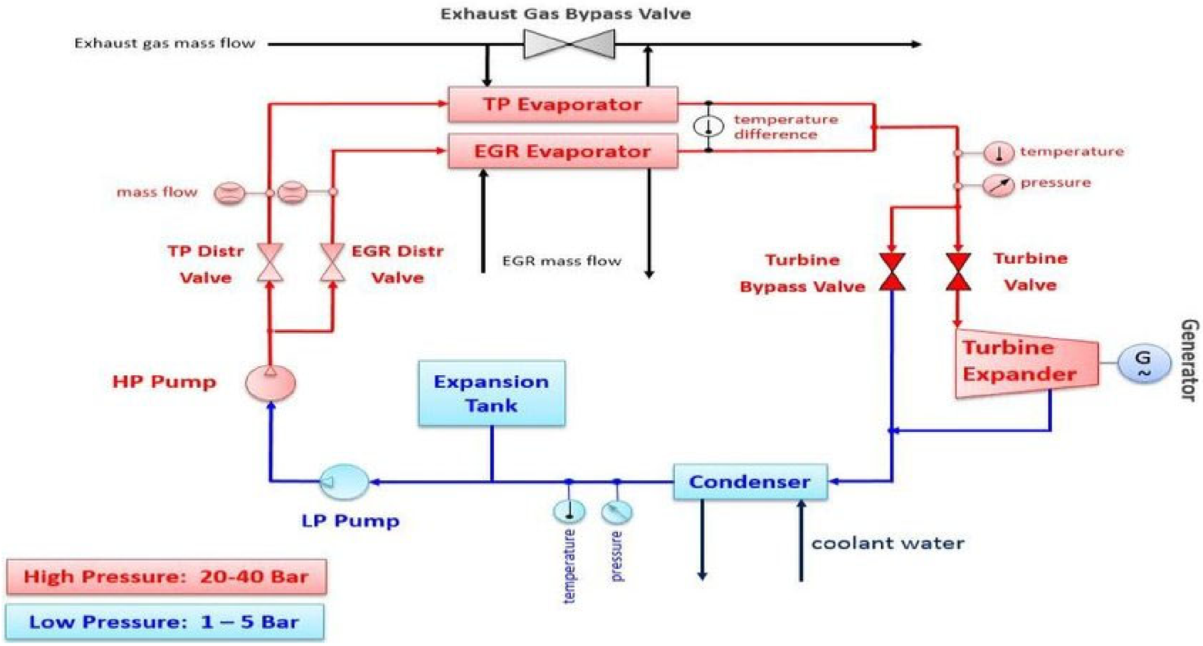

FIG IV. ORC-WHR SYSTEM MODELLING [18]

EGR is an abbreviation for "Exhaust Gas Recirculation." The EGR system is designed to recirculate exhaust gases back into the combustion chamber in internal combustion engines. This is intended to lower the combustion temperature of the engine, aiding in the control of nitrogen oxide (NOx) emissions.

In a study focused on ORC with waste heat recovery comparing thermodynamic and thermoeconomic performance for different working fluids in the low to medium temperature range, n-butane stands out with the highest overall efficiency (5.22%) thanks to thermodynamic optimization. Thermoeconomic optimization ranks n-butane as the most cost-effective option, with a specific investment cost of 2136 €/kW. The costs considered reflect retail prices in Belgium.Thermodynamic optimization favors lower evaporating temperatures, while thermoeconomic optimization leans toward higher evaporating temperatures (e.g., for n-butane, the optimal evaporating temperature is higher in thermoeconomic optimization than in thermodynamic optimization) [12]. In the waste heat recovery system for a chemical/petroleum tanker with a maximum useful volume, where waste heat is extracted from four different sources, namely Model 1 from jacket cooling water, Model 2 from scavenge air, Model 3 from exhaust gases, and Model 4 from a combination of all sources, utilizing the refrigerant R245fa, the total thermal efficiency of the ship's power plant can be increased by up to 1% using Model 1, 3.4% using Model 3, 4.2% using Model 2, and 6.7% using Model 4. This improvement is achievable in the marine Organic Rankine Cycle (ORC) Waste Heat Recovery (WHR) system. The combined Waste Heat Recovery System (WHRS), Model 4, demonstrates the highest power output and contributes significantly to the thermal efficiency of the ship's power plant. For the selected ship, an annual fuel saving of up to 704 tonnes is achievable with the implementation of the combined Organic Rankine Cycle (ORC)-based WHRS, Model 4. This integrated ORC WHR system, Model 4, is capable of fulfilling all navigational electricity demands without the need for auxiliary sets when the engine operates at approximately 82% MCR (Maximum Continuous Rating) or higher.Despite the high initial capital costs associated with ORC WHR systems, they exhibit a short payback time. Through the amalgamation of waste heat sources, the payback time for ORC WHR systems can be reduced by up to 46.8%. [19]. A study involves the design and simulation of an ORC (Organic Rankine Cycle) circuit using Cycle Tempo software. Five different fluids, namely Isobutane, R11, R12, R245fa, and R113, are analyzed, comparing various input parameters such as Engine Exhaust temperature vs Power, Condenser pressure vs Power, and

Boiler Pressure vs Power. The system demonstrates net electrical power outputs of 8.21 kW (Isobutane), 6.27 kW (R11), 5.46 kW (R12), 5.68 kW (R245fa), and 6.62 kW (R113). Isobutane emerges as the most efficient working fluid for ORC, recovering heat from Engine Exhaust, with the highest net electrical power output of 8.21 kW [20].

V. RESULTS AND DISCUSSIONS

In the evaluation of different working fluids within the Organic Rankine Cycle (ORC) Waste Heat Recovery (WHR) system, Isobutane, R11, R12, R245fa, and R113 exhibited varying performances. Notably, Isobutane emerged as the most efficient working fluid, showcasing the highest net electrical power output at 8.21 kW. This outcome is attributed to Isobutane's favorable characteristics, such as high vapor density and critical temperature, making it a superior choice for maximizing power generation.The comprehensive comparison of waste heat sources, including jacket cooling water, scavenge air, exhaust gases, and their combination, revealed distinct impacts on the overall efficiency of the ORC WHR system. The combined Waste Heat Recovery System (WHRS), Model 4, demonstrated the highest power output, contributing significantly to the thermal efficiency of the ship's power plant. This model also allowed for an annual fuel saving of up to 704 tonnes, emphasizing its environmental and economic advantages.The study reaffirms the short payback time associated with ORC WHR systems, despite their high initial capital costs. The integration of waste heat sources, as exemplified in Model 4, further reduces the payback time by up to 46.8%, highlighting the economic viability of such systems.The ORC WHR system's ability to meet all navigational electricity demands without auxiliary sets, particularly when the engine operates at 82% MCR or higher, positions it as an efficient and sustainable solution for marine applications. This achievement not only reduces thermal pollution but also fosters energy conservation, contributing to the overall environmental sustainability of the ship's power plant.In conclusion, the results underscore the significance of fluid selection, waste heat source integration, and operational conditions in optimizing the performance of ORC WHR systems. Isobutane, combined waste heat sources in Model 4, and the system's capability to meet navigational electricity demands without auxiliary sets stand out as key contributors to enhanced efficiency and sustainability. These findings provide valuable insights for the design and implementation of ORC WHR systems in diverse industrial contexts.

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