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ORGANIC RANKINE CYCLE AS WASTE HEAT RECOVERY: A REVIEW OF THEIR POTENTIAL APPLICATIONS

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ABSTRACT

Increasing emissions of carbon dioxide and fuel prices lead to extra efforts in finding solution to reduce the environment waste heat. One of the solutions emerging is the Organic Rankine Cycle (ORC) system. It is one of the promising exhaust heat recovery technologies which is widely been used to recover low to medium-grade heat rather than conventional steam Rankine cycle system. This paper highlights on the different applications ORCs that are usually been applied. These different applications have different constraints and usually different configurations will be considered based on the applications.

Keywords: organic Rankine cycle; preheater; supercritical; superheating; waste heat recovery

1.0 INTRODUCTION

As higher efficiency of industrial technology is in demand, more and latest technologies are needed to produce energy. Increasing of population growth [1] and escalating process of electricity are mostly due to emission gases from the industry, vehicles, deforestation and others. In the aerospace industry, engineers continuously search for new methods to upgrade the efficiency of the engines. Recovery waste heat could increase the engine efficiency [2]. Although society undergoes global issues, social problems or economy crisis, this does not stop the industry from expanding which leads to increase in demand of fuel this result in increasing of fuel price since more conventional fuel is needed and causes pollution into the environment [3]. Still, the price in this development is used to optimize the engine. In each flight, greater revenue could be achieved when the number of passengers is greater. And to have more passengers, lighter aircraft is needed. It is important to note that weight is very crucial in changing aircraft engines as it connects linearly with the amount of fuel used in every unit of force powered by engine (specific fuel consumption). Waste heat recovery (WHR) is one of the most important solutions found to lower the emission and fuel consumption [4]. Waste heat or low- grade waste heat is heat energy produced in the atmosphere through internal combustion. However, these low-grade waste heats are not sufficient enough to generate power due to insufficient low temperature. Thus, to recover these waste heat, Organic Rankine Cycle (ORC) system is one of the beneficial exhaust heat recovery technologies which is widely utilized in the applications of low-grade heat recovery rather than conventional Rankine cycle [5]. By combining an ORC with energy system, for instance in power plants, organic fluid of low boiling point is utilized to change heat into electricity. The organic fluids or refrigerants used in air conditioning systems accumulates (collect) heat from a volume of air and release it to different type of heat exchanger which increases the expansion of high vapor pressure in expander. The heat accumulated is transformed into mechanical power or electricity and therefore will help to increase the thermal efficiency and the overall performance of the engine. Because of its thermodynamic properties, organic fluid is the best selection for low quality heat sources with temperatures below than 100 ºC [2]. Thus, designing a fuel-efficient and cheaper heat exchanger, ORC power plant can effectually utilize the economic and environmental issues.

2.0 ASPECTS OF WASTE HEAT RECOVERY SYSTEM

Based on second law of thermodynamics, the efficiency of a process would not be 100 % as there is no process that can entirely transform all amount of heat into work. The energy that is not used to produce work is being dissipated as heat at different temperatures, levels streams. On aircraft, half of the fuel energy lost through this way. Nevertheless, these sources of waste heat are everywhere; from this lost energy, only a part of it can be used to produce mechanical work or other purposes, where around 30% of the total waste heat could be changed to useful work. As the demand of aircraft is increasing vastly, the aviation industry has been the world center of attraction as new technologies are needed and maximum exploitation of fuel is a must. The conversion of heat energy to mechanical or electrical power depends on the characteristics of the source. Let say in an air conditioning system, an external hose is two or three degrees above the ambient temperature, it is a waste to recover that little amount of energy, however, this power leak will be an irreversibility process together with other similar leaks will decrease the thermal efficiency. This is called as waste heat and is an unused heat energy produced as a by-product of process of energy transformation, as a natural consequence on any non-adiabatic process from the thermodynamics law. Most of the available waste heat is low waste heat that can be used by an ORC which utilizes low boiling point organic fluid as working fluid, for example, toluene, hexane or pentane. Presently, there has not been any waste heat recovery (WHR) system added to an aircraft. Nevertheless, researchers suggest on adding WHR system to future engines and propose to make changes in current engines. However, it is a hassle to change the actual design of the engine as more expenses will be used in research, tests and certifications and a lot of heat source needs to be taken into account. Pasini et al [6] analyzed the possibilities of heat recovery results in overall efficiency of an aircraft engine. A waste heat recovery system is modelled in a jet engine and a turbo propeller engine. Their project takes into account the nozzle works in off design state. The heat emitted influences greatly in the system performance. They also developed a numerical thermodynamic code to evaluate the positive impacts of waste heat recovery in a turboprop, a turbofan and a turbojet. The turbofan engine is of great interest due to large fraction of thrust is provided by cold flow, whilst gas generator supplies needed power. The authors then concluded that the enthalpy level ahead of exhaust nozzle of gas generator could be decreased without losing a lot of thrust. From the results of the calculations, it was found an increase of thermal efficiency about 4% when heat recovery was done (efficiency of regeneration was 0.5). At the same time, if the efficiency was 0.7, an increase of 10 % was achieved. From the numerical simulations, the best place for heat recovery is from hot gas before entering nozzle. Another research done by Li et al. [7] was to study the small-scale ORC system performance with low grade heat sources to provide electricity in various working state. The experiment setup includes normal ORC system components, for instance, turboexpander with high speed generator, finned tube condenser, ORC pump and plate evaporator. Results found that the turbine power and condenser heat output, ORC pump power and evaporator heat input, turbine isentropic, overall efficiencies and system thermal efficiencies rises when heat source temperature rises too. The fluid of ORC during superheat and pressure at turbine inlet were two crucial variables that kept constant with temperature heat source and pump speed of ORC.

3.0 ORGANIC RANKINE CYCLE (ORC)

The concept of Rankine cycle was first developed by Prof William John Macquorn Rankine in the 1850s and 1860s. ORC utilizes organic compound instead of water as a working fluid, generally, a refrigerant, a hydrocarbon such as pentane, butane, perfluorocarbon or silicon oil. The organic fluid’s boiling point is much lesser compared to water and enable heat recovering at lesser temperatures instead of the steam Rankine cycle [8]. ORC’s first commercial applications with medium-scale power plants for geothermal and solar applications were developed in the 9 late 70s and 80s. These days, over 200 ORC power plants are recognized with more than 1800 MWe installed and the technologies keep on increasing day by day [9]. Mostly, the plants were installed in biomass combined heat and power (CHP) application, geothermal plants and plants of WHR followed. The layout of ORC is much simpler compared to the steam cycle as there is no water vapor attached to the boiler, and a single heat exchanger could be utilized for the three processes of evaporation including preheating, vaporizing and superheating. ORC can use low-grade heat sources than steam Rankine cycle. Since it could be utilized in lower temperature at the turbine inlet and reduce thermal stresses in the boiler. In regular steam plant systems, the performance cycle is at risk damage due to gaseous infiltrations that occur in sub atmospheric condensing pressure. In steam-based cycle, the usage of a single tube for evaporation is abstained due to large density difference that exists in between liquid and vapor phases. However, some organic fluids have condensation pressure higher than the atmospheric pressures and this avoids the infiltration of non-condensable gases in the condenser. The small differences in density organic fluid phase of liquid and vapor also enables the use of once-through boilers. This led to avoidance of using stream drums and simplified the operation of the whole plant. A simple plant system can be developed and less cost is needed when uses organic fluid compared to steam based cycle. In ORC, usage of deaerator is unnecessary but that is not the case for steam base cycle. Due to presence of oxygen, water deaerator or water

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treatment must be added to avert erosion. Because of low fluid density in the cycle low-pressure part, steam cycle also needs large turbines, heat exchangers and hydraulic diameter for pipes. Meanwhile, since organic fluid has higher density fluid, usage of compact appliances is allowed, especially in marine application, the available space for recovery plant of waste heat is restricted. Other than that, the enthalpy drop in ORC is much lower compared to steam cycle. The process in ORC can be done in a single stage with much simpler turbine compared to steam cycle which requires turbine with some expansion stages. ORC normally operated at much lower pressure levels and rarely exceeding 30 bars. Thus, ORC is beneficial in low to medium power range due to its cycle simplicity, less cost and stress level needed at boiler, easier to control and simpler usage of components [10].

Figure 1 describes the ORC system consisting of an evaporator, a turbine, a condenser and a working fluid pump integrated to a gas turbine engine between exit of low- pressure turbine (LPT) and nozzle. The ORC system begin at the outlet of the liquid side of the pump and used shell-tube heat exchanger evaporator which is convenient for higher-pressure application with several tubes inside and most used in several industries. Heat is the transferred inside the shell through the tube wall by infiltrating one fluid inside the tubes, and the other fluid flows outside of the tubes.

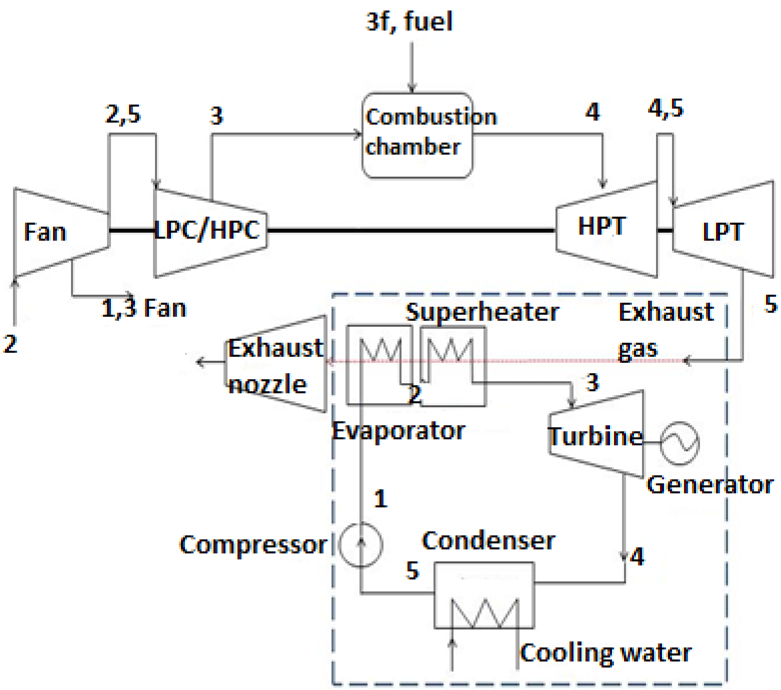

Figure 1 ORC system schematic diagram integrated to a gas turbine engine [11]

3.1 Application of Organic Rankine Cycle

The ORC technology has been utilized broadly and applied in various industrial activities especially in biomass and geothermal application. Nevertheless, ORC technology has been increasing in solar thermal system and heat recovery applications from industrial waste heat.

(a) The combined heat and power (CHP) of biomass

There is widespread use of agricultural or industrial processes such as lumber or agricultural waste in biomass due to low energy density than the fossil fuels and availability of heat and electricity, where biomass is suitable on off-grid case or unreliable grid connection. Local generation results in smaller power plants that exclude traditional steam cycles that in this power range are not profit-making.

Figures 2 and 3 define the working principle of such cogeneration system, at a temperature from 150 ºC to 320 ºC, heats from combustion is transmitted from the flue gases to the heat transfer fluid in two heat exchangers. When temperature lowers a little bit below 300 ºC, heat transfer fluid (thermal oil) is sent to the ORC loop to evaporate the working fluid. Then, the evaporated fluid expands, to preheat the liquid using recuperator and when temperature reached 90 ºC, the fluid condensed to produce hot water.

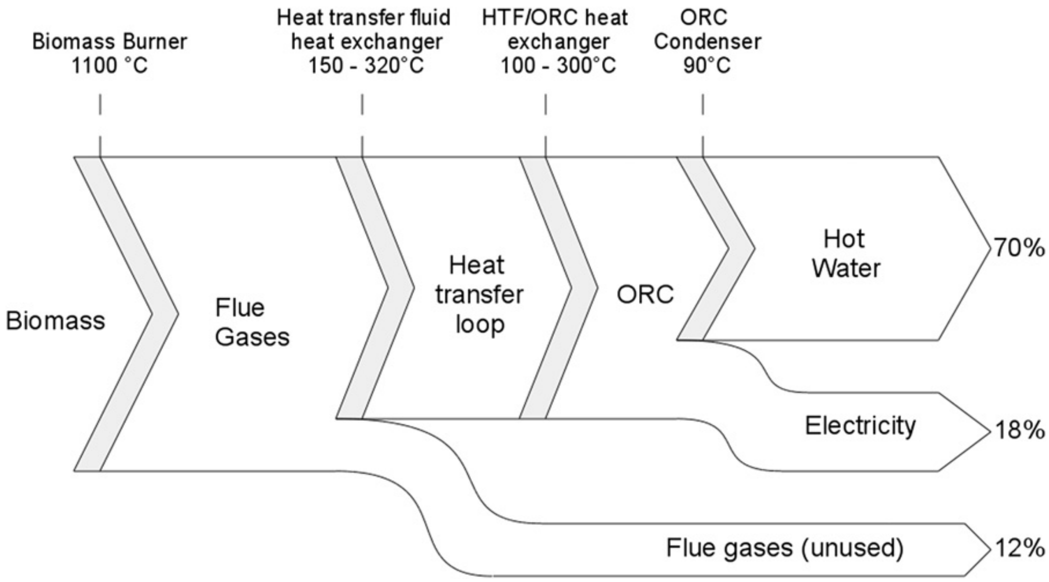

Figure 2 Energy flows in a CHP system of biomass [12]

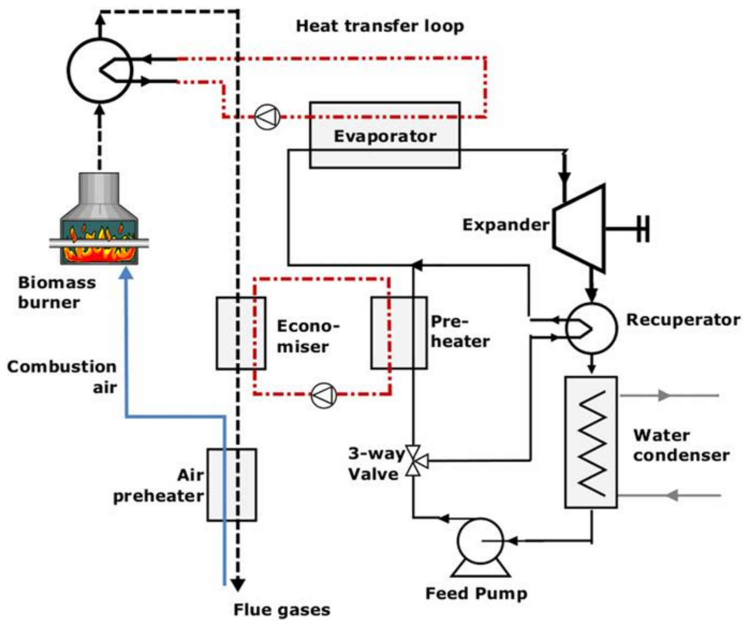

Figure 3 Biomass CHP ORC system working principle [12]

ORC efficiency is lesser compared to traditional steam cycles and gradually reduces for small scale units. To raise the overall energy conversion efficiency of plant, heat demand is needed and could be met through space heating or industrial processes (wood drying). Load of plant could be managed through on- site heat request or maximize power generation which includes additional wasting heats but increases, the full load operating hours per year.

From Figure 2, even though the CHP system's electrical efficiency is somewhat less (18 %), the overall system efficiency is 88 % greater than centralized unused flue gases most residual heat is lost. These gases need to be cooled to the least possible value, so that acid dew point could not be achieved and to lower the losses in flue gases. Two heat transfer loops are utilized to achieve this point (high and low temperature). The lower temperature loops are installed after the high flue temperature to lower the outlet temperature. Competitive technology in generating electric out of solid biofuels is biomass gasification where biomass changes into an organic gas mainly consisting H_2, CO, CO_2 and CH_4. In order to remove solid particles, this synthetic gas is treated and filtered and finally burned in an ICE or in a gas turbine. Contrasting Biomass CHP's technology and costs with an ORC with gasification, gasification yields higher investment costs (75 %), higher maintenance costs (200 %) and more power-to-thermal ratio, where utilization is increase profit-making. ORC is an established technology meanwhile gasification plants are normally used as prototype in operation.

(b) Geothermal energy

Geothermal heat sources ranges from 10 ºC to 300 ºC. The actual lower technological limit to generate electricity is about 80 ºC, and became less efficient with temperature less than 80 ºC and causes uneconomical geothermal plants. The potential of geothermal energy in Europe is shown in Table 1 and indicates that low temperature sources have higher potential.

Table 1 Geothermal energy potential in Europe for different temperature ranges of heat sources [13]

Temperature	**MWth**	**MWe**
65-90 ºC	147736	10462
90-120 ºC	75421	7503
120-150 ºC	22819	1268
150-225 ºC	42703	4745
225-350 ºC	66897	11150

For better production and injection, boreholes need to be drilled in the ground (Figure 4) to recover heat at an acceptable temperature. Then, the hot brine is pumped out of the first one and injected at a lower temperature in the second. Boreholes might be few thousand meters deep which results in working continuously for few months depend on the configuration of the geology and causes increasing share of drilling for geothermal plant cost investment (up to 70 %) [13]. High auxiliary consumption is also characterized by low geothermal ORC: the pumps ingest 30 to 50 % of the gross power output [14]. The brine pump together with a significant flow rate has to circulate the brine over large stances is the primary consumer. Working fluid of pump consumption is greater than higher temperature cycles, as the ratio of pump consumption to turbine output power ('back work ratio') rose as evaporation temperature lowered. Geothermal heat sources temperature (>150 ºC) is allowed for a combined heat and power (CHP) of geothermal, where the condensing temperature is restricted to a higher temperature such as 60 ºC, enabling district heating uses cooled water. Thus, the overall efficiency of energy recovery rises with lower electrical efficiency expenses.

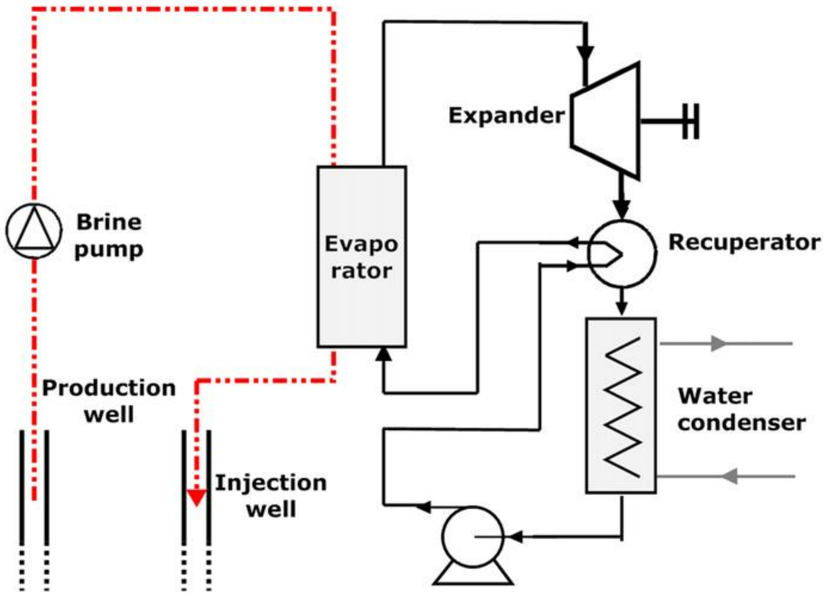

Figure 4 Geothermal ORC system working principle [12]

(c) Solar power plants

Solar power concentration is the best technology on a linear or punctual collector that tracks and reflects the sun, transferring heat to high temperature fluid. Electricity is generated as heat is transmitted to a power cycle; electricity is generated. The three primary technologies of concentration are the parabolic platform, solar tower and the parabolic trough. Punctual concentrating technologies consist of parabolic dishes and solar towers, results in more concentration factor and greater temperatures. For solar towers, the Stirling engine (small-scale plants), the steam cycle or even the combined cycle is the best suited power cycles. Parabolic troughs operate at lesser temperature (300 ºC to 400 ºC). Till today, they were combined to traditional steam Rankine cycles to generate electricity [15]. Geothermal or biomass power plants for example, steam cycles need higher temperatures, pressure and installed power to be more cost- effective. Organic Rankine cycle is a favorable technology that could lower the small scale of investment costs by working at lesser temperatures and reduce total installed power to kW scale. The working principle of the system is shown in Figure 5.

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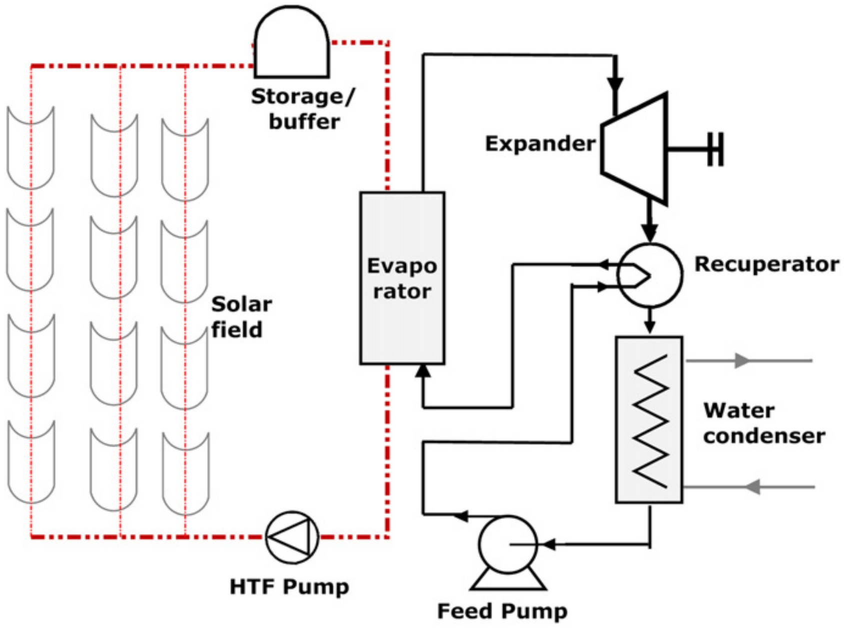

Figure 5 Solar ORC system working principle [12]

Till recently, only a few of CSP plants with ORC are accessible on the market:

- In 2006, at Arizona, a 1MWe solar concentration of ORC power plant was accomplished. The ORC module utilizes n-pentane as the working fluid with 20 % efficiency. On design point, the overall solar energy efficiency is 12.1 % [16].
- Few small-scale for the applications of remote-off grid were studied. The only proof of concept obtained is that 1KWe system installed for rural electrification in Lesotho by "STG International". To produce and integrate small size solar thermal technology with medium temperature collectors and an ORC to acquire economics equivalent to big installation of solar thermal is the objective of this project. This design intended to change or adding diesel generators in developing countries at off-grid areas through generating clean power at lesser costs.

(d) Mechanical and industrial heat recovery

At low temperature, most of the application in manufacturing industry reject load. Normally, the heat is enormous in large-scale plants, and could not be used again for on-site district heating. The heat then discharged into the atmosphere and results in two types of pollution [17]:

- Health/ Environmental issues results from pollutants (CO_2, NO_X, SO_X, HC) of flue gases.
- Unbalance of aquatic equilibrium and negative effector biodiversity due to rejection of heat.

These two types of pollution could be diminished by waste heat recovering. Moreover, it could provide on-site electricity to be consumed or sent it back to the grid. Normally, waste heat is recuperated through an intermediate heat transfer loop in such a system and used to evaporate the cycle's working fluid. In US, power generation from industrial waste heat sources is approximately about 750 MWe [18]. Some industries have greater potential in recovery of waste heat. One of it, the cement industrial loses 40 % of flue gas heat. These flue gasses are placed at a temperature of 215 ºC to 315 ºC after the preheater of limestone or in the clinker cooler [19]. CO_2 released from the cement industry is 5 % of the world's total CO_2 emissions, half of the results from fossil fuels combustion in kilns [16]. Further possible industries include iron and steel industries (for example, 10 % of CO_2 emissions in China), refineries or chemical industries. Although their potential is higher and cost-effective (1000 €/kWe - 2000 €/kWe), ORC recovery waste heat cycles have only 9 - 10 % of the world's installed ORC plants compared to biomass CHP and geothermal units [9].

(e) Aircraft engine

Perullo et al. [20] integrated an ORC to an engine for power generation. They mentioned the problem, as bypass ratio keep on growing and the engine cores becomes effective, the diameter of engine fan increases and the core size decreases which causes pneumatic offset needing greater percentage of the core flow and results in higher performance penalties. They tried to solve the problem by changing the pneumatic off-take to an electrical and used power generated to drive external air to the Environmental Control System (ECS). With the idea of no-bleed aircraft, performance penalties for shrinking cores and increased fan diameter are supposed to be eliminated and they had demonstrated that a rise in efficiency from 0.9 % to 2.5 % is possible. Boeing has also applied the no-bleed system; but using generator as the source of energy, not ORC where the generator works with energy taken from the APU and engines. As this application save fuel by 3 %, this explain why they put this idea together in ORC rather than extracting energy from fuel, the waste heat could supply the energy needed. ORC is used due to the low quality of the range temperature. The WHR system is placed in the core jet exhaust of a turbofan engine. Conversely to land ORC systems, used in steam power plants for instance, an on-board ORC would suppose operating conditions that may vary continuously in the course of every few hours in external pressure and temperatures. The amount of heat extracted from the engine should be considered to avoid reduction of thrust. The system is distributed in the nozzle, the nose cowl and the Pylon. It uses R245fa as the working fluid having demonstrating highest thermal efficiency in a wide range of operating pressure. The MathCAD 2001 software was used to model the design to govern whether energy is enough to extract our f the exhaust gases to a power of 270 hp motor. Figure 6 below describes the ORC schematics with the numbers represent the locations where the temperature are being measured.

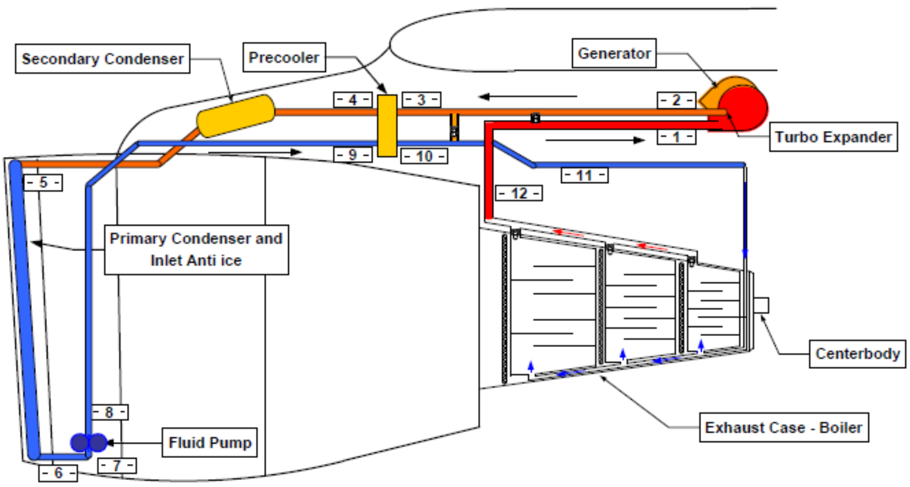

Figure 6 Aircraft engine ORC system working principle [19]

The model was integrated on a CFM56-7B configuration and cruise conditions were used in it. Some assumptions were done; not analyzing the system with take-off conditions as working fluid dissociates at high temperatures, heat is taken out of core exhaust flow before expanding in the nozzle, assuming a weight of 430 kg and was used to calculate the fuel burn reduction (0.9%) a TSFC reduced its value in 2 % compared to the engine alone. It was also assumed that the ORC could produce greater power which is needed to drive the ECS air compressor and resulted in reduction of TSFC for 22 %. C.A. Perullo et al. [19] concluded that an ORC WHR system could produce more power on the existing engine and can be utilized to supply sufficient power to a compressor driving air to the ECS. They suggested that the design system should be reconfigured to obtain the best results of fuel burn and take into account the need of an electric starting mechanism if the bleed system was removed in future research. The option of using the engine cowl or the anti-icing system in the wing s as the condenser of the ORC system was suggested as well.

3.2 Different configurations of Organic Rankine Cycle (ORC)

(a) Organic Rankine Cycle (ORC) with regenerator (RORC)

Regenerative ORCs are designed where ORCs and turbine bleeding are integrated to a heat exchanger. The cycle heats up the working fluid upon infiltrating the evaporator which is almost similar to the ORC with recuperator. Figures 7(a) and 7(b) provide the schematic cycle and T-s diagram of regenerative cycle. The system consists of an evaporator with preheater, a turbine, a condenser and a working fluid pump integrated to a turbofan engine between exit of low- pressure turbine (LPT) and exhaust nozzle. When entering the evaporator, the preheater heat up the organic fluid for a better thermal efficiency. Figure 7b shows the below shows the T-s (temperature-entropy) diagram of the ORC with superheater and preheater Instead of wasting the heat extracted from the nozzle directly into the air, the heat recuperated and ducted into the evaporator. The transfer of heat in the exchanger to the

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organic fluid helps in cooling down the hot gas from the waste heat with organic fluid as the cold fluid this time.

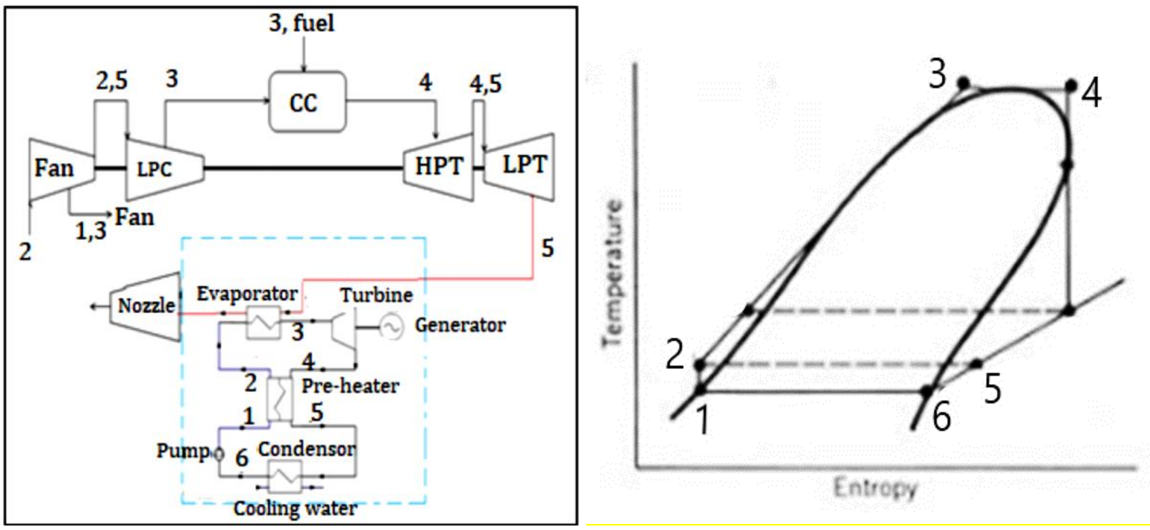

Figure 7 (a) ORC with regenerator and its T-s diagram [11]

At 139 ºC of turbine inlet temperature, Le et al. [14] utilized a genetic method to optimize the first law and effectiveness of the system for diverse fluids. When examining, CO_2 results the worst while recuperative cycle was discovered for greater efficiencies compared to simple cycle. Moloney et al. [21] studied the environmental fluids with critical temperature below 200 ºC in regenerative supercritical ORCs to upgrade the geothermal energy efficiency and noted that CO_2 operates the lowest. The same purpose was enforced by Muhammad et al. [22] to the basic ORC; single and double stage regenerative ORC for applications of recovering waste heat. Studies showed that the single and double stage regenerative ORC has greater thermal efficiency with lower economic performance rather than the basic ORC.

(b) Organic Rankine Cycle with superheating

Found that superheating of dry fluid negatively affects the ORC's efficiency while wet fluid positively affects the ORC's efficiency and isentropic fluid did not really affect ORC. Nevertheless, an experimental observation by [23] indicated that ORC with wet fluid superheat utilizing R245fa at 1.8ºC and if the superheat rises to 8.7ºC, the system is stable. Thus, even for dry working fluid, superheating is essential.

Li et al. [24] conducted an experimental study to inquire the performance of a small-scale ORC system with low grade heat source to produce electricity at various working state. It was found that the fluid of ORC during superheat and pressure at the turbine inlet were two main variables able to be managed with temperature of heat source and speed of the ORC pump. It was also found that superheat and internal heat exchanger are crucial for ORC from both perspectives of thermodynamic and techno-economic. Roy et al. studied the consequences of superheat and recovering on ORC system at certain degree of superheat [25]. Note that Guo et al. [23] argued if the superheat coupled with an internal heat exchanger, greater development could be done. Zhang et al. inquires the consequences of superheat and internal heat exchanger on three ORC designs' thermos-economic performance from fluid properties and heat sources. It has been discovered that the thermo-economic performance of internal heat exchanger ORC with dry surpasses the wet fluid as temperature of heat source load increases [26]. Brizard et al. [27] suggested preventing condensation drops during operation of superheating; the inlet of expander must exceed 20ºC. Radulovic et al. [28] mentioned that superheat is important in cycle especially in wet fluids. As the temperature of superheater rises, the cycle efficiency also rises and the chance of the working fluid condenses during pressure drop inside turbine, resulting in corrosion and efficiency drop is lesser. To get a higher efficiencies and net power output, superheating is important to prevent wet expansion. Feng et al. [29] found that rises the superheat degree assure the decrease in mean heat transfer temperature difference in superheating area of evaporator causes decreasing of overall heat transfer area and decrease in the investment cost of the system. It was also found that outlet temperature of evaporator and superheat degree gives good feedback on the efficiency of exergy. Li et al. [24] construct an investigation on the experimental of a small-scale ORC system under designated working state for the recovery application of low-grade thermal energy. The reaction between condenser cooling water temperatures and superheat R245fa at turbine inlet were measured and analyzed on the performance of the system. The outcomes show that when evaporating pressure is constant, superheat at the inlet of expander gives negative feedback on the turboexpander and performance of the at some temperatures of cold water. In conclusion, superheat is crucial in assuring an efficient and safe system operation. Bianchi et al. [30] presented an experimental micro-ORC setup for low-temperature application by implementing a test bench to acquire data for the energy system characterization. From the results, it was found that for the tested working points, efficiency is from 2.9 % to 4.4 % and increases as degree of superheating decreases. Ismail et al. [31] concluded that utilizing superheated vapor in the system with internal heat exchanger results in increasing of thermal efficiency ORC. The mass flow rate required for the system together with superheated vapor is lower than the saturated vapor system. Thus, superheated is essential to lower the mass flow rate, and enhanced the performance of the system with presence of internal heat exchanger.

4.0 CONCLUSION

This article presented a comprehensive review on the developments of Organic Rankine Cycle (ORC) systems that have been used for power generation by using a waste heat source. This review also highlights more on the different applications of ORCs used as waste heat recovery system. From here, we could conclude that using ORC as waste heat recovery has a very wide benefits and should be more explored in various types of applications. Therefore, for future work it is planned to investigate the design of an ORC model with better output power by selecting the best configuration available and also to study the effect of using ORC as waste recovery system in an aircraft engine.

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