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The performance of Organic Rankine cycle for recovering waste heat

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Abstract-*In this study, the feasibility of using ORC system for waste heat recovery was investigated using mixed research methods. A case study of AL-Zour station in Kuwait was selected to perform this investigation. The obtained results of analyzing the collected data from the case study showed that; the orc can be effectively used to reduce the waste energy by generating electrical power, where different types of orc turbines are analyzed in this research.*

Keywords- ORC system, qualitative analyses, Quantitative analyses; waste heat recovery, station data.

I. Introduction

In developed countries, up to 40% of the total fuel consumption is used in space and process heating in both domestic and in the industries [1]. Studies have shown that up to a third of this goes to waste. As the demand for energy efficiency has been continuously increasing, it has led to interests in heat recovering systems. Consequently, there have been increasing demands for devices that can convert the excess heat into electricity. It has become possible to generate electricity from thermal sources at low temperature by using organic liquids, rotating turbines and other expanders using similar principle as that of steam cycle. Organic Rankine cycle (ORC) is a name that has been adopted to describe this process of low heat extraction [3]. The process uses fluids that are highly efficient when they are used for low power generation with heat at low temperature.

The ORC suits in such application, mostly because of its capacity to recover low grade heat, and the possibility of being applied in decentralized power plants with low capacities [2, 3]. For steam cycles to be profitable, they need to operate at high temperature and pressure, and therefore need high installed power. ORC on the other hand, is an affordable system for low power, and low temperature systems, where steam systems are costly. The ORC is conceptually the same as the steam Rankine cycle because there is vaporization of liquid at high pressure liquid, which is then expands to reduce the pressure, so that mechanical work is released [3]. The cycle ends at the condenser, where the low pressure vapor is condensed and pumped back at high pressure. Similar components to those used in the conventional steam power plant are also used in the ORC (boilers, work producing expansion devices, condensers and pumps). The difference is in the working fluid, which is characterized by a lower boiling point than that of water.

Because of the low molecular weight of water, multistage expanders are required in order to achieve higher efficiency in the cycle. In contrast to this, all the working liquids used in the ORC systems have higher molecular weight and boils at a lower temperature. The fluids also have lower critical pressures and temperature than that of water. For ORC engines operating at extreme temperatures below 200^0C, using higher molecular weight fluids achieves higher cycle efficiencies in simple and less expensive single-stage expanders [3].

The ORC systems have potential benefits on the amount of energy used in industrial processes especially in re-gaining the heat that would otherwise go to waste (waste heat). When an ORC is installed to convert the waste heat into energy, this improves energy use efficiency. This is an approach called combined heat power generation (CHP) through

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bottoming cycle [3]. The ORC has proved to improve the energy consumption of buildings by using CHP. Fossil fuels produce high levels of temperature, while ORC can use this high temperature to generate electrical energy. At the same time, the low heat that the ORC rejects is still useful in meeting the heating requirements of the building. This is an approach called combined heat and power generation through topping cycles [3].

Applications of Rankine can also be extended to converting renewable heat source into electrical power. These include solar, geothermal and biomass resources. The ORC generally uses single-stage turbines or similar expansion devices like scroll and screw expanders to produce energy. It is therefore very applicable in trough type solar CSP systems that use steam turbines to produce electrical power. These generate heat in the temperature ranges that the ORC operates more efficiently than the steam cycles.

II. *CHARACTERISTICS OF SIMPLE RANKINE CYCLE*

A simplified Rankine cycle is an idealized closed vapor cycle which has four stages according to the figure below.

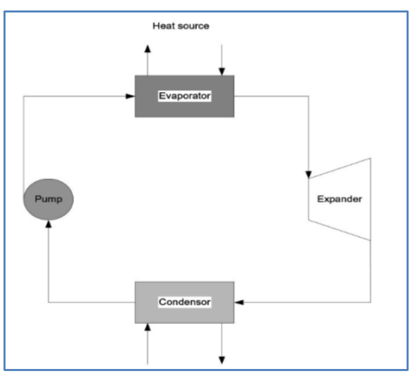

Figure 1:A Schematic of a Simple Rankine Cycle system [4].

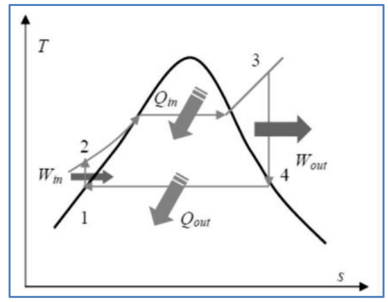

Figure 2: A T-S diagram of Simple Rankine Cycle [4]

Thermodynamic curves (such as vapor saturation curves, P-h, and the T-S curves) are used to describe the Rankine cycle the figure 2 above is an example using a P-h curves [4]. A simple Rankine cycle undergoes four main stages [3, 4]. In stage 1-2, the organic working fluid is forced by pump to move from a lower to higher pressure. The pump uses only a small amount of energy since the fluid is a liquid. In stage 2-3, the fluid which is at high pressure enters in the boiler and is heated by an external heat source, while the pressure remains constant, to a dry and a saturated vapor. In process 3-4, this dry saturated vapor enters an expander, where it expands, and produces power. During this process, the vapor temperature and pressure decreases, and some condensation occurs. In process 4-1, the wet vapor enters into a condenser and condensing occurs at a constant pressure, forming a saturated liquid.

III. *CHARACTERISTICS OF ORGANIC RANKINE CYCLE*

Organic fluids that are used in ORC possess interesting thermodynamic properties that make them suitable to recover heat from low temperature sources. Some of the characteristics that make organic fluids superior include [3]: 1) lower heat of vaporization, 2) lower temperature of vaporization than water at the same pressure, 3) high specific heat capacity due to lower molecular weight, and 4) some fluids show positive slope of the saturation vapor curve. The first three characteristics allows for the use of lower temperature sources, while the last characteristic allows for the expansion from a non-super-heated vapor point without entering in the vapor area.

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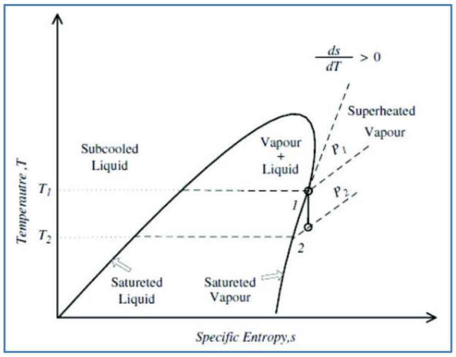

Figure 3: T-S diagram of a non-superheated ORC [3].

Showing positive slope of the saturation vapor curve is very important because there is no need of superheating the fluid since the fluid is still in vapor phase at the end of the expansion. This helps avoid problems inside the expander, especially if a turbine is used. The choice of the fluid in ORC design is determined by the source of the heat. In Rankine Cycle, three different types of fluids are used, and are characterized by the gradient of the T-S curve in the region of saturated vapor [3]. In this region, a wet liquid has a negative sloping curve, and hence has to be superheated so that the vapor remains dry saturated when expanding. Typical liquids in this category include carbon dioxide and water. The wet liquids have to be superheated to avoid formation of droplets in the expansion stage. Dry fluids have positive curve in the saturated vapor region and remains in dry saturated vapor as the expansion process takes place [3, 4]. Anisotropic liquids have infinite curve, and represents an ideal fluid for the ORC.

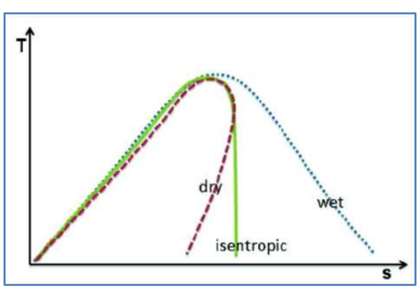

Figure 4: Types of Fluids used in ORC systems [3].

The ORC systems usually use dry anisotropic liquids. These dry fluids are advantageous in that they do not require superheating because they remain in saturated vapor state during expansion [3, 4]. In addition, they produce a higher output power for a given operating temperature. The selection of the liquid for the ORC is depended on the temperature of the heat source to be used. There are a wide range of fluids available so as to match varying temperature sources.

IV. HEAT EXCHANGER TECHNOLOGIES FOR ORC

Studies have noted the counter flow as the most efficient among the three, because its heat transfer is higher.. The main designs of heat exchangers include the shell-and-tube heat exchanger, and the plate-heat-exchanger. The tubes are arranged to form bundles and can be made in different types such as plain tubes, longitudinally finned, among others. The shell is considerably weaker than the tubes to enable circulation of fluid at high pressure in the tubes as the low pressure fluid flows in the shell [1, 2]. By reversing this order, the vapor condensation in small diameters that are parallel to the tubes causes instabilities in the flow. There are a wide range of tube and shell heat exchangers, with different materials are used to make the shells and tubes. The shape of shell and tube heat exchangers make them robust, and are as a result, used for high pressure applications, where pressure exceeds 30 bar and temperatures higher than 260^0C [1].

Improvement of the performance of heat exchangers can be achieved by including fins or corrugations in any of the directions of flow [2]. Aluminium or aluminium alloy is used to make the fins due to its heat transfer efficiency, and contributes to reduced weight of the exchanger. The plate-and-fin heat exchanger has a higher efficiency than that of the plate type, however, this comes at an increased installation and maintenance costs.

V. PERFORMANCE OF ORC SYSTEMS

A. Working Fluids

In Organic Rankine systems, the type of application, and the temperature of the wasted heat

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determines the type of organic fluid to be used in the system [5]. The liquids that have high critical temperatures allow for high boiling points but with lower pressures, and therefore, there is possibility of lower pressures. The organic fluids have relatively lower enthalpy differences than that of water. Consequently, there is huge mass flow for the same amount of power output. To achieve better performance of any ORC system, certain general criteria is used to identify the best suited organic working fluids. These include the stability of the fluid, thermodynamic properties, compatibility with the materials of the ORC, availability, safety, environmental impacts, and the cost [5].

The performance of ORC systems is significantly dependent on the characteristics of the working fluids, and studies have shown that p-xylene achieves the best performance, while benzene has the poorest [5, 6]. In addition, the p-xylene exhibits lower irreversibility at high waste heat temperatures of the heat recovering process, while both R123 and R13 achieves better performance in recovery of low temperature waste heat [5]. Another importance observation with ORCs is that when dry fluids are used, higher efficiency is realized, as opposed to when wet fluids are used. Isentropic fluids achieve almost a constant value for high temperature at the inlet of the turbine, and therefore, they are the most suitable for the recovery of low temperature waste heat.

B. ORC Configuration

The performance of the ORC systems can also be improved by including other components in the configuration. Some of these are discussed below.

1) Regenerator

Regenerator can be included in the initial configuration of the ORC as shown in the figure below. It recovers heat from the superheated vapor before reaching the condenser. This way, the heat duty of the condenser is reduce, while the enthalpy of the working fluid leaving the pump is increased [1, 7]. The end result is that the thermodynamic efficiency of the cycle is improved since there is reduced duty at the preheater.

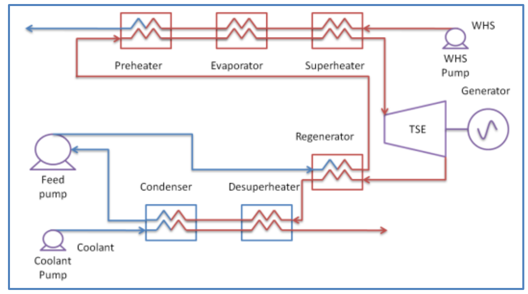

Figure 5: A schematic of a Regenerator [1]

There are two disadvantages of using the regenerators. First, they increase the overall cost of the system, and second, it reduces the recovered heat that from the heat source. Although use of regenerator leads to improved performance, the coverable power is reduced, leading to reduced overall system [8].

This has been a common case with most geothermal power plants. Since geothermal fluids differ in chemical composition from one well to another, it is advisable to estimate individually the temperature limitations for the re-injected water for every installation.

2) Reheating (dual expansion)

The reheating process involves use of two expanders where the working fluid is reheated at specific between the two pressure stages [8]. This pressure is a key parameter considered in the design. Each of the expander is analyzed separately, and assumed to be a single stage expender. The two expanders do not need to have the same efficiency. The difference in the pinch-point temperature constrains the re-heater, just as it happens in the boiler.

Addition of the reheater to the system increases the average heat addition temperature, which results to increased efficiency. Another shortcoming is that there is an added discontinuity in the performance curve created by reheating, which makes it difficult to match capacitance rates of thermal resource and working fluid [1, 8]. Matching of these two is a significant factor in system optimization.

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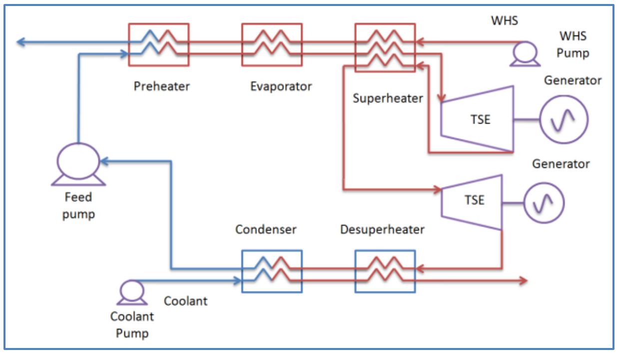

Figure 6: A Schematic of a reheat system [1]

3) Dual cycle system

Dual system is another configuration that can be used to maximize the performance of the ORC systems. This process involves combining the processes and selecting the working fluids. Consequently, the overall cost of such a system is relatively higher [1]. However, the long term benefits of such configurations can out-weigh these short term (installation) costs.

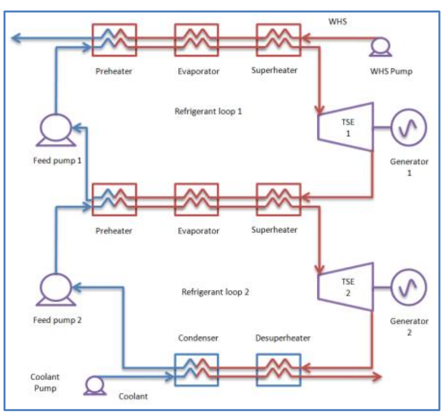

Figure 7: Schematic of a Dual Cycle [1]

VI. Modeling and analysis

A qualitative and quantitative data collection methods were performed at a thermal station located in Kuwait which is known as Alzour thermal station. This station utilizes steam turbines as the key units for power production. At this station, the collected data were for the temperature, pressure and flow rate of the exhausted gas from the steam turbine. The available commercial models for ORC systems in this station were reviewed and analyzed in order to examine their suitability for waste heat recovery. Among the available ORC systems in the Market, one system was selected for this station in order to improve the heat recovery process in this station.

A feasibility analyses for the selected ORC type was then carried out to examine the possibility of using this ORC system in Al-Zour station in term of power generation price and environmental effects.

A. Qualitative and quantitative research methods

Different models of ORC turbines are available in market, where table below shows the Siemens ORC turbines specifications. [9]

Table 1: ORC turbines performance [9]

Module		ORC‑Module 1	ORC‑Module 2	ORC‑Module 3	ORC‑Module 4
Performance					
Power output	kW	400	600	1000	1500
Aux. power consum ption	kW	25	33	52	83
Efficiency		18.4 %	19.4 %	19.6 %	19.5 %
Heat Input ORC‑Module					
High temper ature (HT) circuit	kW	1990	2840	4680	7040
Low temper ature (LT) circuit	kW	180	260	420	640
Sum heat input	kW	2170	3100	5100	7680
Condenser Output					
Heat transfer to heating network	kW	1740	2450	4050	6120

Regarding the suggested power plant the monthly operation for the power plant load is shown in the following figure per each steam turbine [10]

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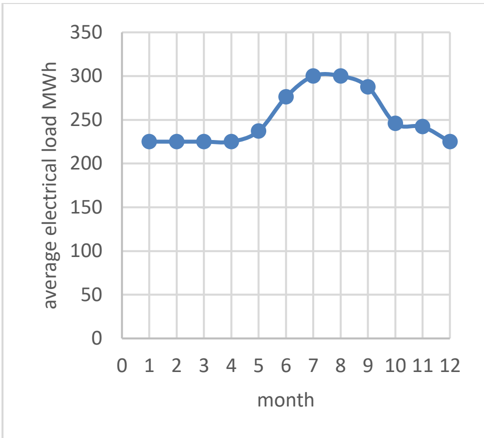

Figure 8: average electrical load MWh

The suggested ORC was assumed to be installed with the steam turbine to recover the waste heat where figure 9 shows a schematic for connecting the ORC turbine with low pressure turbine (LP).

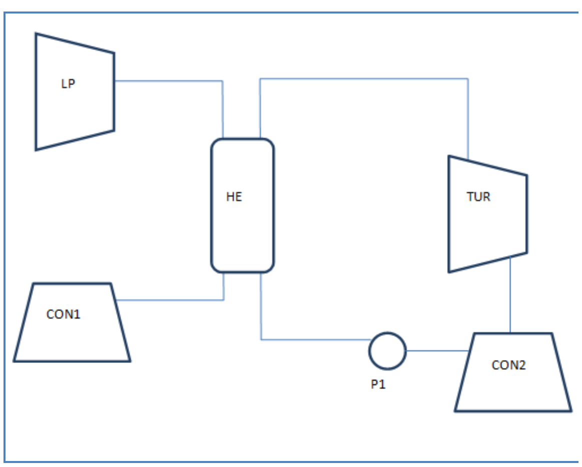

Figure 9: the schematic of ORC turbine with low pressure steam turbine

Figure below shows location of suggested power plant in state of Kuwait using google Earth.

Figure 10: the location of suggested power plant using Google Earth.

the discharge of LP is assumed to be connected with a heat exchanger which will be used to heat the working fluid of the ORC to recover the waste heat. According to selected case study the flow rate at the outlet of low pressure turbine is 265.185ton/hour at enthalpy is 2385.9 kj/kg the available heat is calculated by multiplying the steam flowrate by the heat available which is about 1.76 MW .the amount of heat load can be gained by this system depends on the type of heat exchanger can be used to extract the heat. Shell and tube heat exchanger was suggested to be used for the following reasons

A- the heat transfer will be between two different type of fluid so the mixing is not allowed

B- the shell and tube heat exchangers already used in the plan as re-heaters .

C-the efficiency of this type of heat exchanger is high because they are cross flow heat exchanger up to 45%[], so the amount of heat transfer from the shell side to tube side was calculated at different extraction capacity as shown in the following figure.

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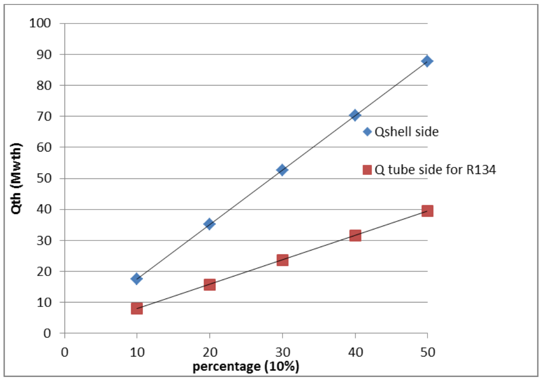

Figure 11: the heat gained by system.

its worth to mention the engineers in the suggested power plant provided that: the extraction line should not exceed 40% because the condenser can deal with losses in piping line up to 40% so the According to table (1) and the thermal requirements for various type of ORC turbines, also assuming the maximum extraction line capacity is 10%. the number of turbines can be used vs. vs the monthly operation power is shown in the following figure

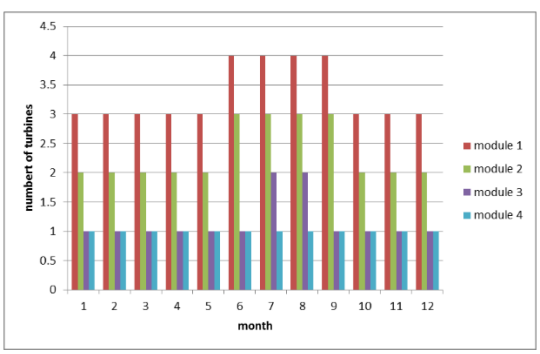

Figure 12: the number of turbines can be used according to monthly operation conditions (10%)

By increasing the capacity of the extraction line up to 20% the following figure shows the number of ORC turbines can be installed based on monthly operation power and the requirements of thermal heat.

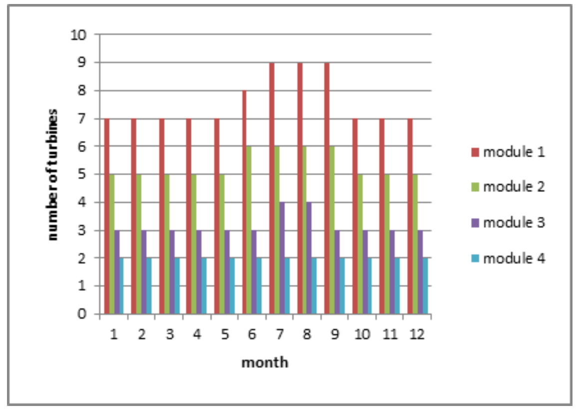

Figure 13: the number of turbines can be used according to monthly operation conditions (20%)

According to the output power of each ORC turbine module, the following figures shows the monthly output electrical power can be extracted using the numbers of turbines .

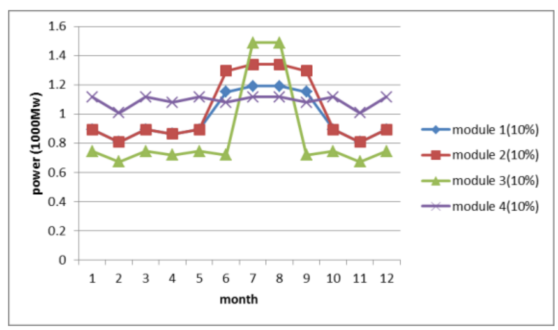

Figure 14: the power extracted according to monthly operation conditions (10%)

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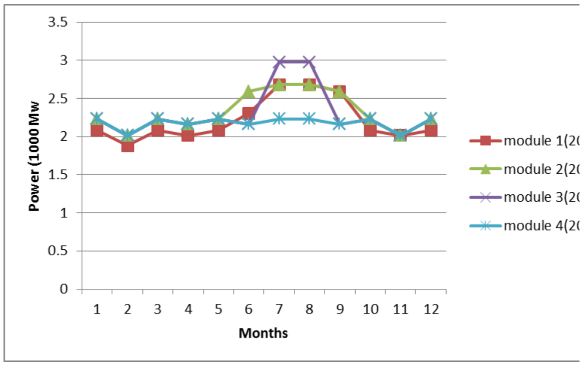

Figure 15: the power extracted according to monthly operation conditions (20%)

The yearly power production can be estimated by finding the summation of power as shown in the following figure , where the maximum power production for the second type of ORC turbines when the extraction capacity is 20%.

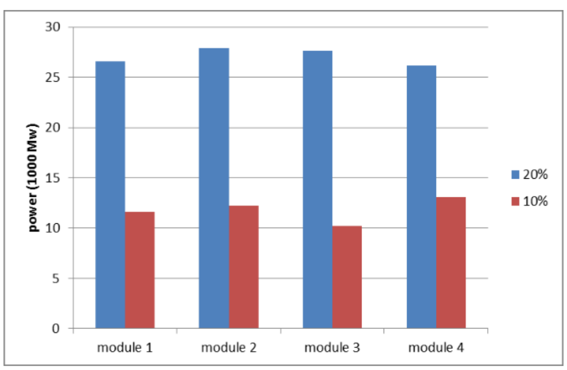

Figure 16: the power extracted according to yearly operation conditions

According to the cost of installing theses turbines due there electrical power is shown in the following figure where the third type has the highest installing cost comparing with other types which is about 120 million KWD .

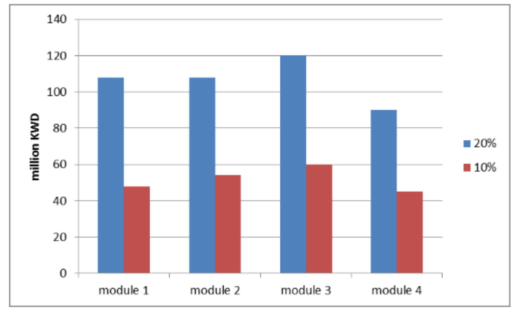

Figure 17: the cost according to the power of ORC turbines

The yearly profit of installing these turbines can be calculated according to power cost in state of Kuwait . according to ministry of electricity and water in kuwat , the production cost for the electrical power about 0.04 KWd/Kw. Using this value the yearly profit for Kuwaiti.

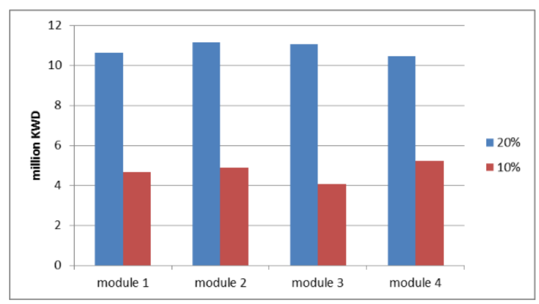

Figure 18: the profit of ORC turbines.

The payback period of the different turbines was calculated according to the installing cost and the profit of each turbine as shown in the following figures. Figure (19) shows the payback period for the first type of orc turbine which able to get profit after 10 years, where the number of turbines can be used with 10% and 20% extraction are 4 and 9 turbines respectively.

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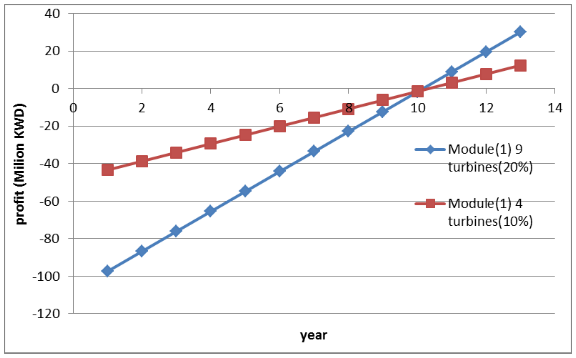

Figure 19: yearly profit of ORC turbine (1st type)

Figure (20)shows the payback period for the second type of orc turbine which able to get profit after 9 year for 20% extraction and 11 years for 10% extraction Where the number of turbines can be used with 10% and 20% extraction are 3and 6 turbines respectively.

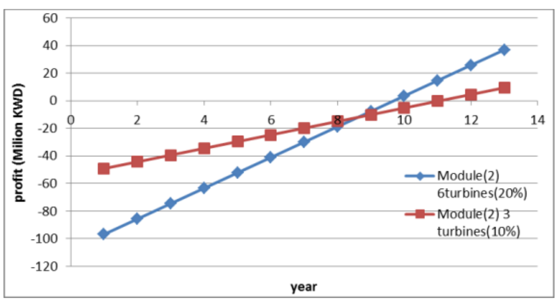

Figure 20: yearly profit of ORC turbine (2nd type)

Figure (21)shows the payback period for the third type of orc turbine which able to get profit after 11 year for 20% extraction and 15 years for 10% extraction, where the number of turbines can be used with 10% and 20% extraction are 2 and 4 turbines respectively.

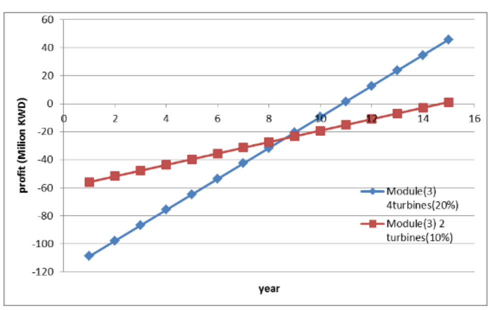

Figure 21: yearly profit of ORC turbine (3rd type)

Figure (22) shows the payback period for the third type of orc turbine which able to get profit after 9 year for 20% extraction and for 10% extraction, where the number of turbines can be used with 10% and 20% extraction are 1 and 4 turbines respectively.

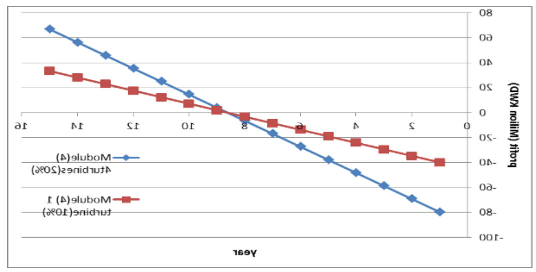

Figure 22: yearly profit of ORC turbine (4th type)

VII. Conclusion

In this project an investigation for the benefit of using ORC turbine to generate electrical power from the waste heat in ORC , where this type of turbine was assumed to be connected to the discharge of the steam turbine in a specific power plant in Kuwait. The student visited the power plant to get useful information about the steam power plant such as the monthly operation and the specifications of turbine discharge, where the calculation is presented according to four types of ORC turbines in market. the results shows the maximum power can be gained by the second model for 20% extraction and for fourth model based 10% extraction , the feasibility of these systems investigated based on the cost of installing and the profit of applying these turbines, it was found the fourth model has the lowest payback period comparing with other types.

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APPENDIX A
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Month	1	2	3	4	5	6	7	8	9	10	11	12
Operation %	75	75	75	75	79	92	100	100	95.9	81.9	80.7	75
Electrical load (MW)	225	225	225	225	237	276	300	300	287.7	245.7	242.1	225