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Feasibility Of Organic Rankine Cycle (Orc) Wıth Waste Heat Recovery

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ABSTRACT

The present study focused on the feasibility of Organic Rankine Cycle (ORC) using waste heat recovery. The waste heat covered from glass factory. The working fluid in the cycle were Isobutane. Thermodynamic model of the system was derived and validated for performance prediction. The validated thermodynamic model is used to optimize the operation of the small ORC in waste heat recovery application. The temperature which recovered and mass flow rate were 155 °C and 27 kg/s respectively. The power output of double stage turbines was 8370 kW .The payback period 2.5 years. It is concluded from the study that recovering the waste heat by way of ORCs is technically and economically feasible. As recycled energy, waste heat has the same advantages as renewable energy.

1. Introduction

Energy demand is increasing more than 40 % since 2000 As a result; there is an urgent need to resolve this growing demand while taking into account the environmental aspect, including the use of waste energy as much as possible [1-3]. The Organic Rankine Cycle (ORC) is steam Rankine cycle ,instead of using steam using low critical temperature organic fluid and it is important technology than renewable energy or waste energy transformed into power[4-6]. Recently, the ORC becoming hot topic and many studies shows the performance improve by change the type of working fluid[7, 8]. There are some advantages of Organic Rankine cycle such as low costs in operation and maintenance, working in low temperature, quiets during the operation, simple start/stop procedures and in some models no water consumption. The world capacity installed is 376 MW from waste heat recovery and 39MW capacity under construction ,using heat from combustion engines or turbines is easier than industrial heat recovery [9].

Topal et al. [10] focuced on optimization of novel dual loop organic Rankine cycle for enhaced of heat from a gas engine, the results showed that 239.82 kW was produced from the cycle with 16.50% energy efficiency. Qu et al. [11] investigated on organic Rankine cycle for marine low speed diesel engine waste heat recovery, the results showed that payback period was 5.2 years and the system was improved.

Last years, waste heat to energy growth up in the world mainly in Turkey and France and become the second market after geothermal. Despite the ability to recover lost heat in cement and iron and steel plants, they represent a very small fraction compared to the use of biogas and the direction to the manufacturers of ORC and offering small units up 200 kW, and this type is desirable in many countries [12-14]. Choose the appropriate fluid is an important point in ORC, the ORC is subcritical cycle. Only dry fluids or isentropic fluids are considering and saturated vapor for inlet turbine[15]. The working fluid should have critical temperature and higher than 150 C°. Isobutane have the critical temperature and pressure 134.7 C°, 36.4 bar [1].

2. System Design

In this study, the Organic Rankine Cycle based turbine is proposed for electricity generation, and the working fluid in ORC is Isobutane. Heat source in this study is waste heat recovery from glasses factory.In state 1 Isobutane enters to high pressure turbine and expands isentropically and returns back for reheating at constant pressure to the heat exchanger. After reheating enters into low pressure turbine, and expands isentropically then converting the mechanical work into electricity [16]. In state 5 the Isobutane enters to the pump as saturated liquid then compressed isentropically. In state 6 the compressed liquid enters to heat exchanger and leaves at state 1 as superheated vapor.

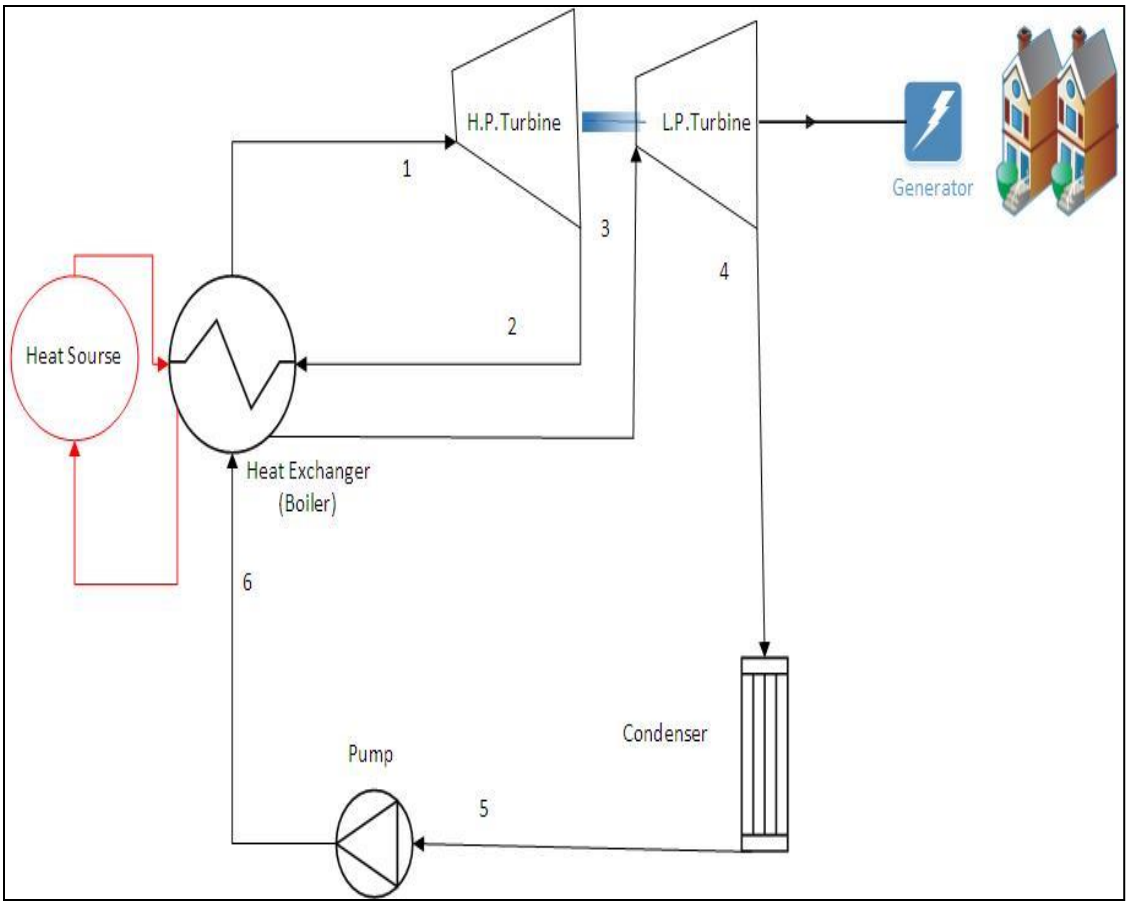

Figure 1: Diagram of Organic Rankine Cycle

In state 4 steams enter to the condenser with lower pressure and temperature. Isobutane usually in the state of saturated liquid –vapor mixture and rejects heat then leaves as saturated liquid from the condenser [17].

3. Energy Calculation

In Organic Rankine Cycle, energy calculations were presented, for all equipment by using the entrance and exit thermodynamic properties, and using Engineering Equation Solver (EES). The energy balances equations are shown for the system as below:

3.1 ORC Heat Exchanger

In this component, heat is transferred from heat source (glass factory) in high temperature to high pressure turbine ORC then reheated to inter low pressure turbine.

Energy heat ($\dot{Q}_{ORC\ he}$), can be calculated as below:

$$\dot{Q}_{ORC\ he} = (\dot{\mathrm{m}}_1 h_1 - \dot{\mathrm{m}}_6 h_{6)} + (\dot{\mathrm{m}}_3 h_3 - \dot{\mathrm{m}}_2 h_2) \qquad \text{(kW)} \qquad (1)$$

Where, $\dot{\mathrm{m}}$ is the mass flow rate, and h is the enthalpy.

3.2 ORC High Pressure Turbine

In state 1 enter to the turbine as super-heated and exit at state 2 after the expansion.

Work output of the HPT ($\dot{W}_{ORC\ hpt}$) is calculated as below:

$$\dot{W}_{ORC\ hpt} = (\dot{\mathrm{m}}_1 h_1 - \dot{\mathrm{m}}_2 h_2) * 0.87 \qquad \text{(kW)} \qquad (2)$$

Where, h is the enthalpy and number 0.87 is the efficiency isentropic of HPT irriversibilities.

3.3 ORC Low Pressure Turbine

The work output of the LPT ($\dot{W}_{ORC\ lpt}$) is evaluated as below:

$$\dot{W}_{LRC\ hpt} = (\dot{\mathrm{m}}_3 h_3 - \dot{\mathrm{m}}_4 h_4) * 0.87 \qquad \text{(kW)} \qquad (3)$$

Number 0.87 is the efficiency isentropic of LPT irriversibilities.

3.4 ORC Condenser

The energy Heat of ORC condenser ($\dot{Q}_{ORC\ cond}$), is written by applying in the equation as below:

$$\dot{Q}_{ORC\ cond} = \dot{\mathrm{m}}_4 h_4 - \dot{\mathrm{m}}_3 h_3 \qquad \text{(kW)} \qquad (4)$$

3.5 ORC Pump

The pump work required ($\dot{W}_{ORC\,pump}$) can be calculated as below:

$$\dot{W}_{RC\,pump} = (\dot{m}_6 * v_6(p_6 - p_5))/0.85 \qquad \text{(kW)}$$
(5)

Where, $\dot{m}$ is the mass flow rate, v is the specific volume and p is the pressure. The number 0.85 is the efficiency isentropic of pump irriversibilities.

3.6 ORC Efficiency

The total work and network for the ORC ($\dot{W}_{ORC\,net}$) can be calculated as below:

$$\dot{W}_{ORC\,total} = \dot{W}_{ORC\,lpt} + \dot{W}_{ORC\,hpt} \qquad \text{(kW)}$$
(6)

$$\dot{W}_{ORC\,net} = \dot{W}_{ORC\,total} - \dot{W}_{ORC\,pump} \qquad \text{(kW)}$$
(7)

Thermal efficiency (η_{th}) of Organic Rankine Cycle is applied in the equation as below:

$$\eta_{th} = \frac{\dot{W}_{ORC\,net}}{\dot{Q}_{ORC\,he}} \qquad \text{(kW)}$$
(8)

3.7 Results and discussions

In the energy analysis of Organic Rankine Cycle(ORC), values of mass flow rate (kg/s), temperature (°C), pressure (kPa), specific enthalpy (kJ/kg), were calculated and results were presented in the table 1.Thermodynamic properties are calculated by using (EES) software. The ORC energetic efficiency is evaluated as 59.27%.

Table 1: Thermodynamic properties of the system at each state

State	T($K°$)	P(kPa)	$\dot{m}$(kg/s)	h(kJ/kg)	S(kJ/kg.K)	v (m^3/kg)
1	428	2000	27	1609	1609	0.049
2	353	50	27	1385	1385	1.79
3	420	50	27	1594	1594	1.982
4	343	80	27	1355	1355	1.1
5	328	80	27	1311	1311	1.073
6	328	2000	27	1295	1295	0.041

In the Table 2 shows the system parameters such as pumps work ORC turbines produced work, energetic efficiency and etc. There are some effect parameters, such as inlet pressure or temperature and those parameters will be in detail as below.

Table 2: Output Values of Components.

Component	Values	Component	Values
WORC$_{HPT}$	5248[kJ/s]	WORCpump	2500 [kJ/s]
WORC$_{LPT}$	5623[kJ/s]	QORC$_{COND}$	1200 [kJ/s]
W$_{TOTAL}$	10870[kJ/s]	QORC$_{HE}$	14123 [kJ/s]
EfficiencyTH	59.27%	W$_{NET}$	8370 [kJ/s]

3.7.1 Effect of network and heat of heat exchanger on the Energetic Efficiency

As it is shown in Figure 2, by increasing the net work and heat of heat exchanger of the system, thermal and heat rate of heat exchanger line goes higher than the net work.

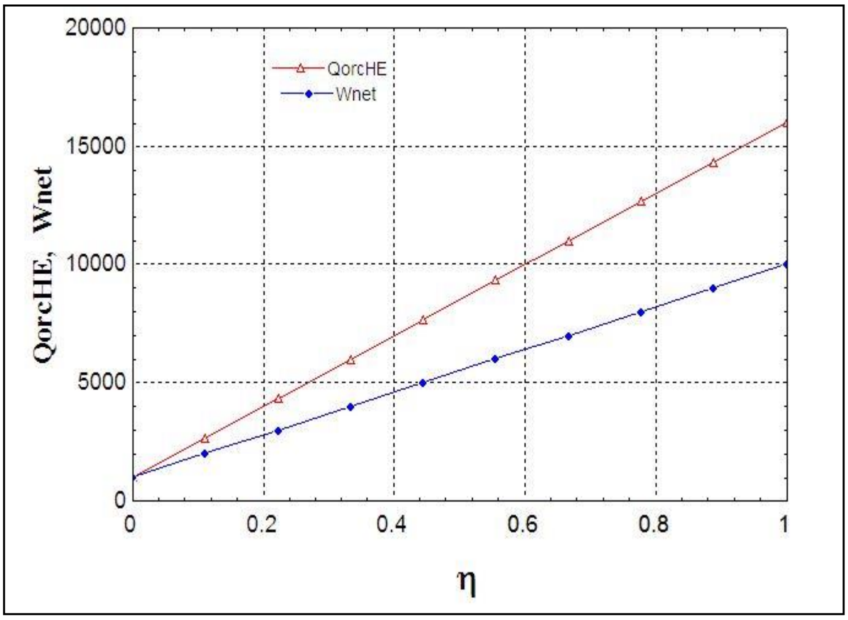

Figure 2.Effect of network and heat of heat exchanger on the Energetic Efficiency

3.7.2 Effect of Organic Rankine Cycle mass flow rate on the high, low pressure turbines, and pump work.

As it is shown in Figure 3, increasing the mass flow rate of the system all the componet low pressure turbine and high pressure turbine producing work are increasing ,also the work of pump is incresing.

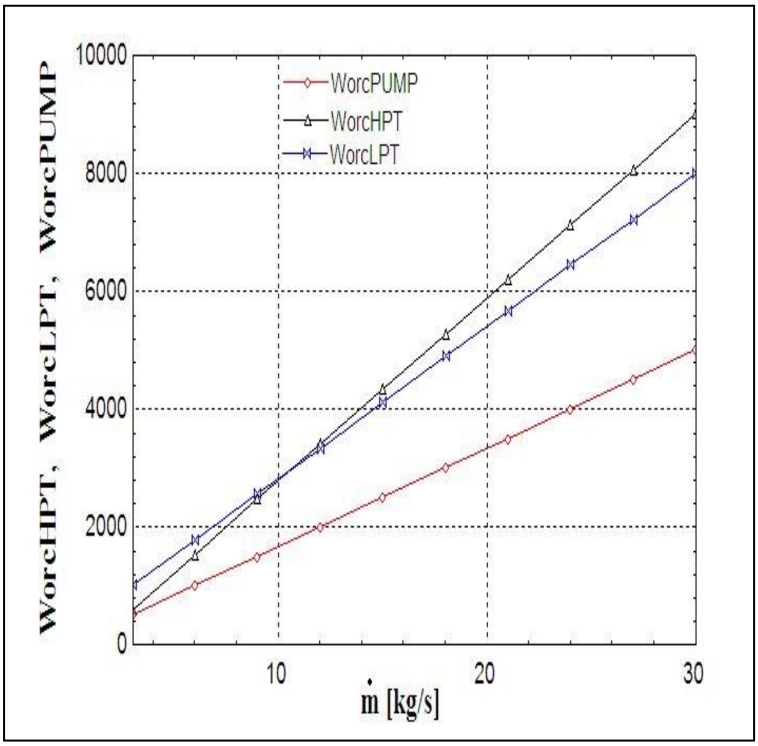

Figure 3 Effect of Organic Rankine Cycle mass flow rate on the high, low pressure turbines, and pump work.

3.7.3 Effect of inlet pressure turbine and pump on the energy efficiency

As it is shown in Figure 4 , increasing the pressure inlet of turbine energetic efficincy is increasing.and the pressure inlet and outlet is low to increase the efficency.

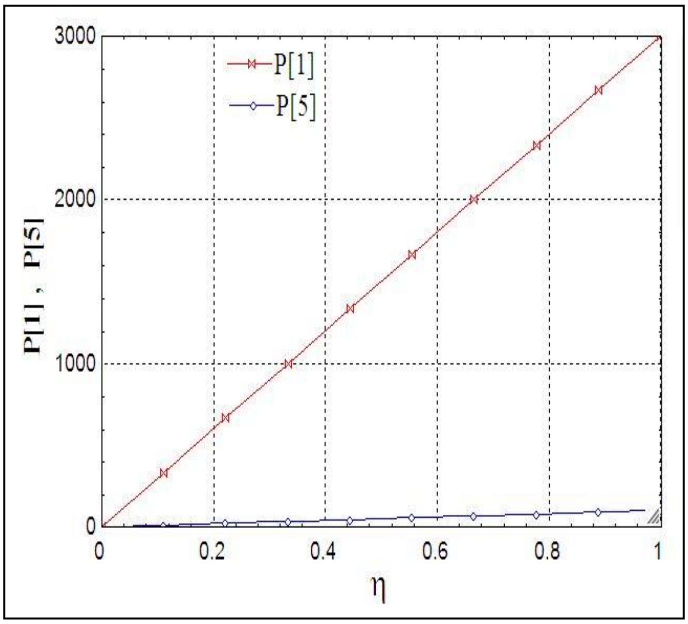

Figure 4 Effect of inlet pressure turbine and pump on the energy efficiency

4. Economic Feasibility

In economic evaluation there are several method are used in energy generation systems, such as net present value (NPV),Internal rate of return (IRR),saving to investment ratio (SIR) will be present in this study[18−20].

4.1 Economic Calculation

Here the formulas which are need for this study as below:

Life Cycle Net Savings (Net Present Value)

$$\text{NPV} = \sum \text{PV Annual Savings} - \sum \text{PV Life Cycle Investment} \quad (9)$$

Savings−to−investment ratio

$$\text{SIR} = \sum \text{PV Annual Savings} / \sum \text{PV Life Cycle Investmen} \quad (10)$$

$$Annual\ Saving = \dot{W}_{ORC\ net} * Working\ hours\ peryear * Cost\ of\ kilo\ watt\ in\ \$ \quad (11)$$

Internal rate of return

IRR = Discount rate, where SIR = 1.0, or NPV = 0

(12)

Simple payback period

SPP = Initial investment / annual savings

(13)

4.2 Results and discussions

In the life cycle cost analysis input for the initial cost, operation and maintenance (O&M), working fluid of organic Rankine cycle, and insurance.

Table 3: life cycle cost analysis in put

Component	Values	Component	Values
Initial cost	23,000,000 $	Annual Savings	9,039,600 $
(O&M),Working Fluid	100,000 $	Discount Rate	3 %
Analysis period (years)	20	Residual value	200,000 $

In the life cycle cost analysis out puts are evaluated and presented as showed in table 4:

Table 4: life cycle cost analysis out put

Component	Values	Component	Values
Net Present Value (NPV)	106693562 $	Savings-to-Investment Ratio(SIR)	4.8
Internal Rate of Return (IRR)	36 %	Simple Payback (years)	2.5

The NPT (net present value) shows money we get it this project and must be positive, and the absolute feasibility in terms of money. The SIR (savings-to-investment ratio) is 4.8 which is more than 1, shows the project make more money than costs. The IRR (internal rate of return) is 36% and by this percentage make more clear how much will earn in project investment. In this study, the simple pay back will be 2.5 years and acceptable, and shows this application were feasible.

5. Conclusions

To conclude the feasibility of ORC using waste heat recovery application were proven in economic analysis part and preceded by design ORC and energy analysis. The working fluid selection was Isobutane show promising results for use as working fluids in organic Rankine cycles, and permit high power outputs. In component models using to predicts the performance of the cycle. Net Present Value, Savings-to-Investment Ratio, Internal Rate of Return, Simple Payback, and electricity cost, have been used as economic criteria. In this paper shows, that Organic Rankine Cycle is a successful technology for waste heat recovery applications.

Nomenclature

ORC	Organic Rankine cycle
EES	Engineering Equation Solver
$\dot{Q}_{ORC\ he}$	ORC Heat Exchanger
$\dot{m}$	Mass Flow Rate,
h	Enthalpy
$\dot{W}_{ORC\ hpt}$	ORC High Pressure Turbine
$\dot{W}_{LRC\ hpt}$	ORC Low Pressure Turbine

$\dot{Q}_{ORC\ cond}$	ORC Condenser
$\dot{W}_{RC\ pump}$	ORC Pump
$\dot{W}_{ORC\ net}$	ORC Net Work
η_{th}	Thermal Efficiency
NPV	Net Present Value
IRR	Internal Rate of Return
SIR	Saving to Investment Ratio

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