Modelling of a Cascade Organic Rankine Cycle Powered by Exhaust Gas of Benghazi Cement Factory, Libya

Ramzi A. Alabeedi[1], Salah A. Masheiti[2], Awad S. Bodalal[3], Magda R. Masood[4], Abdulhamid A. Elsharif[5]

[1]Faculty of Engineering, University of Derna

[2, 3, 4]Faculty of Engineering, University of Benghazi

[5]College of Industrial Technology, Misurata
[1]r. alabeedi[at]uod. edu. ly
[2]salah. masheiti[at]uob. edu. ly
[3]awad. bodalal[at]uob. edu. ly
[4]magda. masood[at]uob. edu. ly
[5]a_shariff66[at]cit. edu. lye

Abstract: ***We all know that, renewable energy sources such as: solar, wind, geothermal, tidal, and waste heat recovery systems (WHRS) are sustainable and environmentally friendly sources of clean energy. In this paper hot exhaust gases, which were produced by one of Benghazi Cement factories production lines at an elevated temperature of 300 °C and at mass flow rate of 5660 m^3/min, were utilized to power a cascade organic Rankin cycle for electricity generation purposes. In order to fully utilize this wasted energy, a thermodynamic model was schematically constructed using a commercial software package called IPSEpro. The model (using two environmentally friendly refrigerants (R - 123, R - 245fa)), was successfully simulated and validated to produce 1030 kW of electricity at reasonable cycle thermal efficiency of 5.6 %, and also to minimize emissions of harmful gases to the atmosphere.***

Keywords: Heat recovery; Benghazi Cement factory; R - 123; R - 245fa; Cascade organic Rankin cycle; IPSEpro

1. Introduction

Industrial facilities could greatly benefit from exploitation of any readily available high potential exhaust gases sources. These sources could contribute to solving some local problems and could also motivate local societies to share the world's concern about producing clean green energy (even at small - scales), and reducing the growing demand for electrical power generation, rising cost of fuel and the environmental restrictions on thermal pollution. The advantages of using waste heat recovery systems from exhaust gases are: low cost, wide range of safe applications and multistage utilizations.

An organic Rankine cycle (ORC) system, using an organic fluid instead of water as the working fluid, is potentially feasible in heat recovery systems and is particularly favourable in temperature applications. However, the selection of working fluids and operation conditions are very important to system performance. The thermodynamic properties of working fluids will affect the system efficiency, operation, and environmental impact, Examples of these refrigerants are: CFCs, HFCs, HCFCs. [2]. The technology developed using a (ORC) can operate off any heat source, with minimum of 51ºC temperature difference between heat source and sink [6]. Recent developments, in the field of organic fluids and the effectiveness of heat exchangers, encourage some large industrial enterprises to start producing complete skid mounted ORC plants. As listed by Schuster [3] there have been about seven ORC - plants manufactures all over the world. For instance TURBODEN®, European leader in ORC technology, produces turbo - generators in range of 500 kW and 20 MW and currently has more than 30 plants in operation [7] at low cycle efficiencies of 5 - 12%.

The selection of suitable organic working fluid is a key factor in low temperature Rankine cycles and is determined by the application and waste heat level [3, 5]. It has been reported that thermodynamic properties of organic fluid and operating conditions have great influence on cycle thermal efficiency. This efficiency is very sensible to heat transfer inefficiencies that caused by low heat input into ORC system [4]. Therefore the higher the molecular mass of organic fluid the higher the heat recovery, hence less unit equipment cost.

The energy source for this study was exhaust gases which were produced by Benghazi cement factory. The factory is located 15 kilometres west of Benghazi. The exhaust gas chimney delivers 5660 m^3/min of gases at a temperature of 300 ºC. The cascade ORC units are configured to fully utilize these exhaust gases supply using two refrigerants (R - 123, R245fa) when the critical temperature approaches to the source temperature. The selection of the most suitable refrigerant was strongly depended on the following four main factors: Heat source temperature range, low environmental impact, safety, and thermodynamic and physical properties. The physical and environmental dates of these refrigerants are summarized in table 1.

Table 1: Physical and Environmental data summary for R - 245fa and R - 123

No	Description	Refrigerant	
		R - 245fa	R - 123
Physical properties			
1	Molecular mass, (kg/kmol)	134.05	152.9
2	Critical points	154 ºC 36.4 bar	183.68 ºC 36.62 bar
3	Boiling temperature at 1 atm (ºC)	14.6	27.6
4	Safety	Non - flammable	Non - flammable
Environmental data			
1	Atmospheric lifetime	7.6	1.3
2	ASHRAE level of safety	B1	B1
3	Ozone depleting potential ODP	≈ 0	≈ 0.02
4	Net Greenhouse warming potential GWP 100 year (2100)	1020	77

2. Modelling Tool

Computational modeling and simulation have become the most basic part in most of nowadays studies and applications. In this research work, simulation commercial software called IPSEpro of Sim. Tech® was used. It is an extremely powerful package [1]. It is highly flexible and comprehensive for modeling and analyzing processes in energy engineering, chemical engineering and many other related areas. IPSEpro is based on overall balances of mass and energy and is capable of simulating the whole system. In order to perform a thermodynamic analysis for a component in the modeled systems, the principle of mass conservation and the first law of thermodynamics are applied to each individual component. Each component can be treated as a control volume with inlet and outlet streams, heat transfer, and/or work. One of the existing sustainable exhaust gas resources at Benghazi cement factory has been simulated using this software package as shown in Figure 1.

During various modeling stages, a parametric study was carried out to find out the most effective parameters that have great influence on the performance of the cycles. The organic Rankine cycle models were directly validated by ASPEN PLUSE 10.0 carried out by one of the European leader in manufacturing of ORC units, TURBODEN®. In addition, pinch point analysis of the most important equipment of ORC model, evaporator heat exchanger, was conducted. As the most modeled cycle equipment were counter and cross flow heat exchangers, all related effectiveness (ε) and Number of transfer units (NTU) explicit relations were used to confirm their validity and to make sure that these components are within acceptable manufacturing ranges.

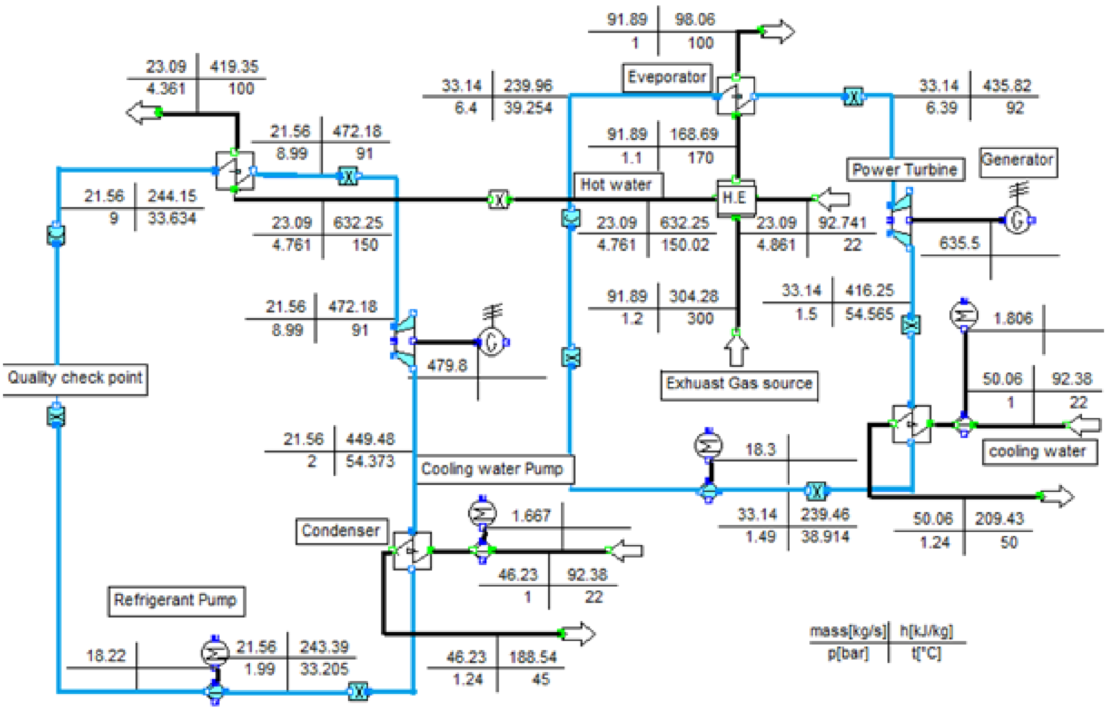

Figure 1: Direct electricity generation by R - 123, R245fa Cascade Organic Rankine cycle model

2.1 Modelling Basic Equations

The actual expansion of the working fluid through the turbine, with an isentropic efficiency of 80%, to convert heat energy into power:

$$W = \dot{m}_{wf} * (h_1 - h_2) * \eta_m * \eta_S$$

With a condensation process occurred within counter flow heat exchanger using cooling water at 22ºC, the heat transferred to the cooling water (heat out) is:

$$Q_{co} = \dot{m}_{wf} * (h_2 - h_3)$$

The work done by the working fluid pump:

$$W_P = \dot{m}_{wf} * (h_3 - h_4) / \eta_P$$

The heating process in the evaporator where exhaust gas heat transferred to the working fluid:

$$Q_{ev} = \dot{m}_{wf} * (h_1 - h_4)$$

The net electrical power produced by the ORC unit is:

$$W_{unit} = (W_T - W_{WFP} - W_{CWP})$$

The net thermal efficiency of the ORC unit is:

$$\eta_{Net} = \left(\frac{W_{unit}}{Q_{ev}} \right) * 100$$

3. Simulated Models Results and Discussion

Benghazi cement factory could only benefit from their exhaust gas to directly generate electricity if a cascade organic Rankin cycle (ORC) was adapted. And only two refrigerants, R - 123 and R - 245fa, were the most suitable refrigerants among other available refrigerants due to restrictions of critical conditions. The selected refrigerants were performed well and gave better results when the critical temperature approaches to the source temperature. During simulation process, R - 123 was found to be the most suitable working fluid when powered the cycle by an exhaust gas of 170 º C, while other cycle, using R245fa, was found to be the most suitable refrigerant when powered by sustainable source, which was hot water at 150 º C that obtained from lowering of exhaust gas temperature of first R - 123 ORC. The simulated results showed that net electrical powers of 590 kW and 440 kW were produced at an ORC efficiency of 9 %, 8.9 % respectively. This is shown in table 2.

Table 2: Output results of both modeled refrigerants

S. No	Description	Working fluid	
		R - 123	R - 245fa
1	Source inlet temperature into cycle evaporator (^{0}C)	170	150
2	Gross electrical output power, (kW)	610	460
3	Refrigerant pump power consumption, (kW)	19	18.9
4	Plant net output electrical power, (kW)	590	440
5	Cooling water pump power consumption, (kW)	1.87	1.73
6	Refrigerant power turbine ΔP (P_{inlet} - P_{outlet}) (bar)	4.89	6.99
7	Refrigerant mass flow, (kg/s)	33.14	21.56
8	Cooling water mass flow, (kg/s)	50	46.2
9	Condenser heat transfer, (kW)	5857	4443
10	Evaporator heat transfer, (kW)	6489	4916
11	Cooling water outlet temperature, (ºC)	50	45
12	Source outlet temperature from evaporator, (ºC)	100	100
13	ORC thermal efficiency (%)	9.0	8.95

The total results obtained from simulated cascade organic Rankin cycle model is shown in Table 3, using refrigerants (R - 123, R - 245fa) perform well and gives better results and can be used to operate the ORC in order to produce of electrical power utilized to generate power for Benghazi Cement factory.

Table 3: Output results of Cascade Organic Rankine cycle

Cascade ORC thermal efficiency	%	5.6
Total Plant net output electrical power	kW	1030
Total Cooling water pumps power consumption	kW	3.6
Total cooling water mass flow	kg/s	96.2
Total Refrigerant pump power consumption	kW	37.96

4. Sensitivity analysis of Proposed model

First model of Organic Rankine cycle using R - 123 was found to be communicated with the environment at only two points namely; the exhaust gas source and the cooling water sink. The cooling water temperature is assumed to be fixed at 22 ºC, and the only external variable that will most likely affect the performance of other cycle parameters such as: net produced power, cycle efficiency, refrigerant mass flow, evaporator and condenser effectiveness and NTU values is the heat source temperature. Figures 2, 3, 4 and 5 shows the effect of the variation of the exhaust gas input temperature on various cycle parameters, when UA values of the evaporator and the condenser are fixed at 94 and 621.8 kW/K respectively.

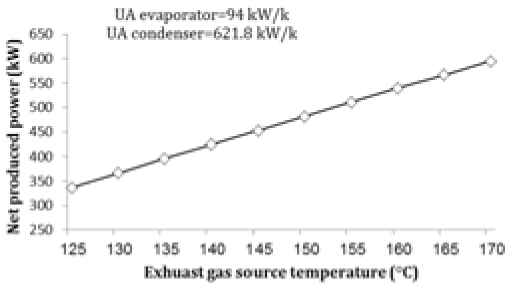

Figure 2: Effect of exhaust gas source temperature variation on net output power

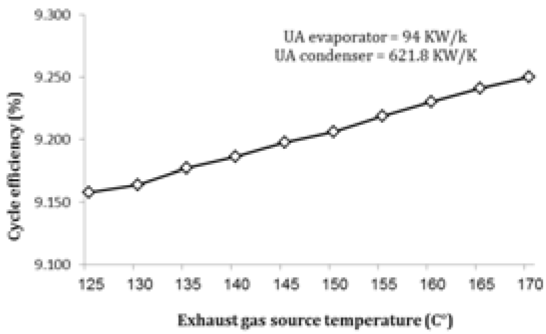

Figure 3: Effect of exhaust gas source temperature variation on cycle efficiency

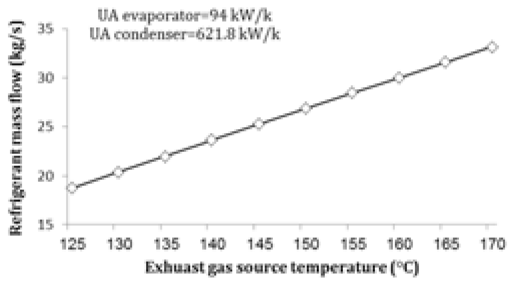

Figure 4: Effect of exhaust gas source temperature variation on refrigerant mass flow

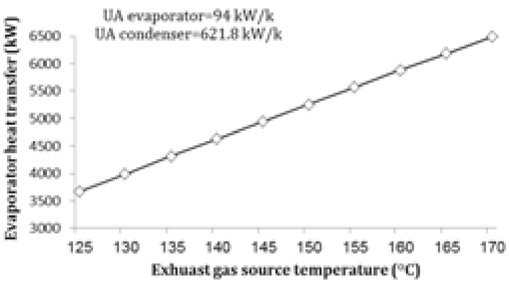

Figure 5: Effect of exhaust gas source temperature variations on evaporator heat transfer

Figure 6 and 7 shows the variation of the evaporator effectiveness and NTU versus the variations of the source temperature at different power turbine inlet temperatures and at constant condenser UA value. For all of the three modeled, power turbine inlet temperatures 91, 92, and 93 ºC there is a gradual decrease in the evaporator effectiveness and the NTU. Because the higher the exhaust gas source temperature, the higher the refrigerant flow rate.

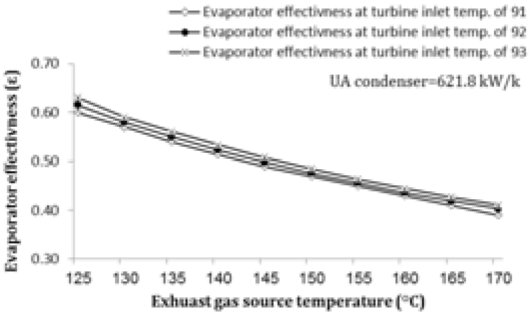

Figure 6: Variations of evaporator effectiveness versus source temperature

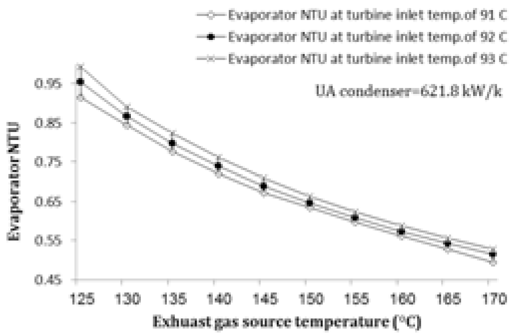

Figure 7: Variations of evaporator NTU versus source temperature

The variations of the condenser effectiveness and NTU with the variation of the exhaust gas source temperature are shown in Figures 8, and 9 respectively. During the simulation process the evaporator UA value (94 kW/K) was fixed in order to examine the effect of the variation of the source temperature on the condenser performance.

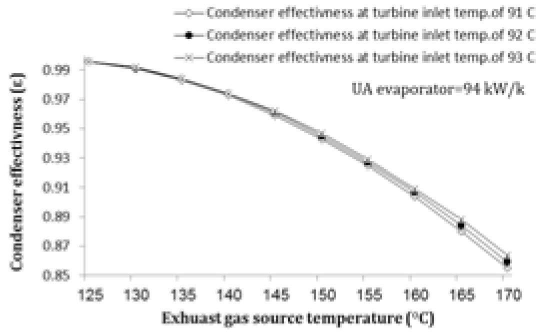

Figure 8: Variation of condenser effectiveness versus source temperature

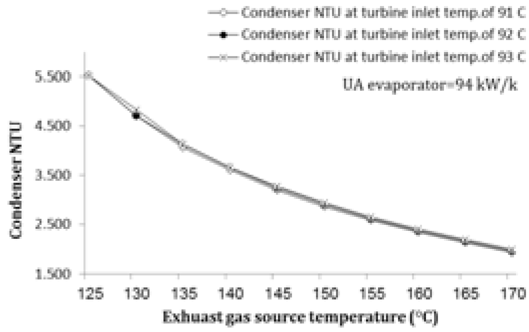

Figure 9: Variation of condenser NTU versus source temperature

The second model, which was using refrigerant R - 245fa, was only affected by hot water source temperature when the cooling water temperature is assumed to be fixed at 22ºC. Figures 10, 11, 12, and 13 show the effect of the variation of the hot water input temperature on various cycle parameters when UA values of the evaporator and the condenser are fixed at 79.06 and 410.11 kW/K respectively.

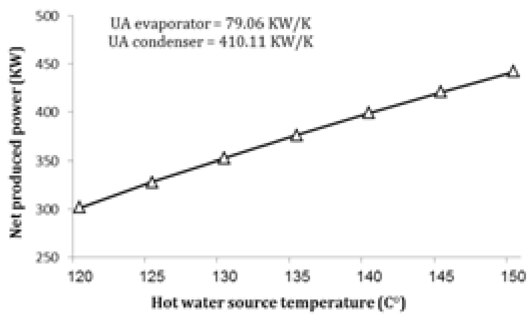

Figure 10: Effect of hot water source temperature variation on net output power.

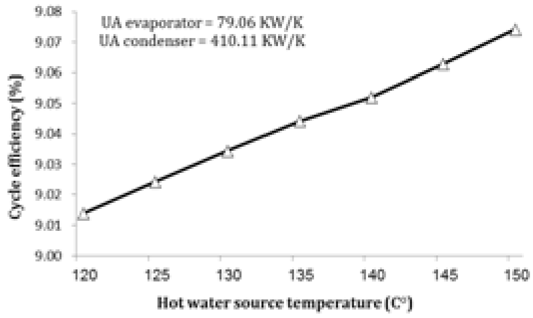

Figure 11: Effect of hot water source temperature variation on cycle efficiency

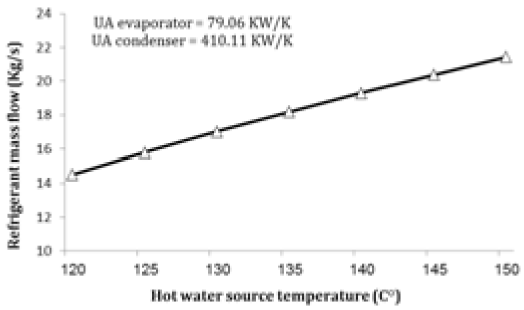

Figure 12: Effect of hot water source temperature variation on refrigerant mass flow

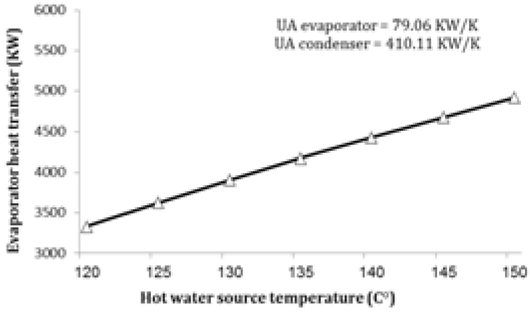

Figure 13: Effect of hot water source temperature variation on evaporator heat transfer

Figure 14 and 15 shows the variation of the evaporator effectiveness and NTU versus the variations of the source temperature at different power turbine inlet temperatures and at constant condenser UA value. For all of the three modeled power turbine inlet temperatures 91, 92, and 93ºC there is a gradual decrease in the evaporator effectiveness and the NTU. Because the higher the hot water source temperature, the higher the refrigerant flow rate.

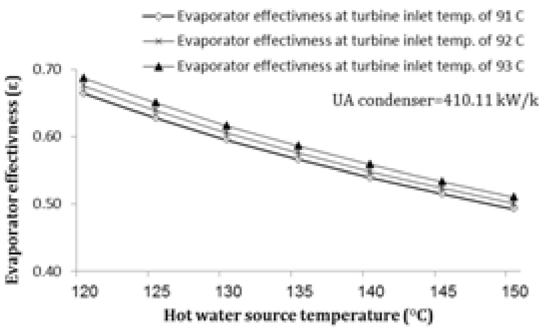

Figure 14: Variations of evaporator effectiveness versus source temperature

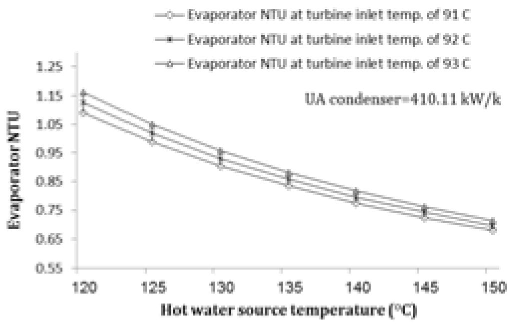

Figure 15: Variations of evaporator NTU versus source temperature.

The variations of the condenser effectiveness and NTU versus source temperature are shown in Figures 16, and 17 respectively. During the simulation the evaporator UA value (79.06 kW/K) was fixed in order to examine the effect of the variation of the source temperature on the condenser performance.

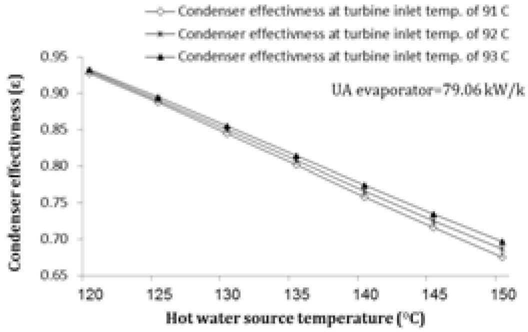

Figure 16: Variation of condenser effectiveness versus source temperature

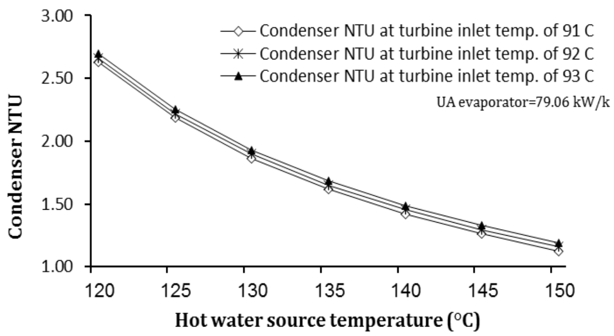

Figure 17: Variation of condenser NTU versus source temperature

5. Conclusions

- Results of simulated models revealed that, using two cascaded organic Rankin cycles, in order to produce electricity, was possible when powered by exhaust gases at 300 °C and 5660 m^3/min.
- Two different types of environmentally safe refrigerants (R - 123, R - 245fa) were found to be the most suitable refrigerants that could be selected for this application. Simulated results showed also that these two cycles could provide 1030 kW of electricity at reasonable thermal efficiency of 5.6 %. The model results were in a good agreement with a model which was built by one of European ORC leading companies, Tuboden® [7].
- Sensitivity analysis reveals that one of the most affected external variables on ORC parameters was degree of cycle powering source temperature when taking condenser cooling source temperature in consideration.
- Producing electricity using waste heat can reduce electrical consumption from national grid supply, which decreases the cost of clinker production and helps the company to be more competitive in market.
- Reducing exhaust gas temperature of Benghazi Cement factory from 300°C to 100°C, by utilizing Organic Rankine Cycle for obtaining electrical power, will reduce emissions of harmful gases to the atmosphere.

Abbreviations	
WHRS	Waste heat recovery system
CO2	Carbon dioxide
SimTech	Simulation Technology
ORC	Organic Rankine cycle
CFCs	Chlorofluorocarbons
HFCs	Hydrofluorocarbons
HCFCs	Hydrochloroflurocarbons
Nomenclature	
NTU	Number transfer units -
Q	Heat transfer kW
T	Temperature ° C
W	work transfer kW
h	Specific enthalpy kJ/kg
η	Efficiency %
m	mass flow rate kg/s
Subscripts	
co	Condenser
ev	Evaporator
m	Mechanical
p	Pump
s	Isentropic
T	Turbine
cwp	Cooling water pump
wf	Working fluid
wfp	Working fluid pump

6. Acknowledgments

We acknowledge the great help of Libyan cement factory for their assistance in this search work.

References

[1] SimTech®. IPSEpro, Refrigeration library manual, 2003, available from http: //www.simtechnology. com
[2] Stowa, Organic Rankine cycle for electricity generation, sheets, Available at: http: //www.stowa - selectedtechnologies. nl /sheets/Organic Rankine cycle, (Accessed 7 December 2009)
[3] Schuster, A and Karellas, S and Kakaras, E and Spliethoff, H, Energetic and economic investigation of Organic Rankine Cycle applications, Applied thermal engineering, Elsevier, 2009, 29, 8 - 9, 1809 - - 1817
[4] Quoilin, Sylvain, Experimental study and modeling of a low temperature Rankine cycle for small scale cogeneration, University de Lige, 2007
[5] Wei, Donghong and Lu, Xuesheng and Lu, Zhen and Gu, Jianming, Performance analysis and optimization of organic Rankine cycle (ORC) for waste heat recovery, Energy conversion and Management, Elsevier, 2007, 48, 4, 1113—1119
[6] Infinity Turbine® LLC, Power generation - Waste Heat, Biomass, Geothermal, Renewable Fuels specifications and data sheets, Available at: http: //www.infinityturbine. com/ORC/ORC_Waste_Heat_Turbine. html. (Accessed 24 March 2009)
[7] Turboden® European leader manufacturer of ORC technology for distributed energy generation web site for Heat recovery from cement production process. Available https: //www.turboden. com/applications/1053/waste - heat - recovery.