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PERFORMANCE EVALUATION FOR THERMAL ARCHITECTURES OF FLUE-GAS ASSISTED ORGANIC RANKINE CYCLE SYSTEMS

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Abstract: Effective use of waste heat at low and medium temperatures is considered as one of the solutions to alleviate energy shortages and environmental pollution problems. Due to its feasibility and reliability, the organic Rankine cycle is continued to attract widespread interest from researchers and/or manufacturers. This paper presents thermodynamic and economic analyses on flue-gas assisted organic Rankine cycles (FGA-ORCs) based on both energy and exergy concepts. The heat source of the FGA-ORC system is the exhaust flue-gas of a stenter-frame which is highly used in textile finishing process. In this study, to convert thermal energy into electrical and/or mechanical energy on a small scale, an optimization study was performed using five different cycle architectures. Parametric studies were also carried out to investigate the effect of operating parameters on performance indicators such as efficiency, economical profit and performance ratio. Finally, under specified operating conditions, the thermal architecture was identified that reduces exergy destruction and increases economic profit due to increased net-work output. For analyzed cases in this study, Scenario-4 (i.e., thermal architecture 4) shows the best system performance with 69% exergetic efficiency within the thermodynamic and practical limits.
Keywords: Organic Rankine cycle, Waste-heat recovery, Flue-gas, Energy analysis, Exergy analysis.

BACA GAZI DESTEKLİ ORGANİK RANKİNE ÇEVRİMLERİNİN TERMAL MİMARİLERİ İÇİN PERFORMANS DEĞERLENDİRMESİ

Özet: Düşük ve orta sıcaklıklarda atık ısının etkin kullanımı, enerji sıkıntısı ve çevre kirliliği sorunlarını hafifletmek için çözümlerden biri olarak kabul edilir. Uygulanabilirliği ve güvenilirliği nedeniyle, organik Rankine çevrimi, araştırmacıların ve/veya üreticilerin ilgisini yaygın olarak çekmeye devam etmektedir. Bu makalede, hem enerji hem de ekserji kavramlarına dayanan baca-gazı destekli organik Rankine döngüleri (FGA-ORCs) üzerinde termodinamik ve ekonomik analizler sunulmaktadır. FGA-ORC sisteminin ısı kaynağı, tekstil bitim işleminde çok kullanılan bir ramöz makinasının egzoz baca gazıdır. Bu çalışmada, termal enerjiyi küçük ölçekte elektrik ve/veya mekanik enerjiye dönüştürmek için beş farklı çevrim yapısı kullanılarak optimizasyon çalışması yapılmıştır. İşletme şartlarının verimlilik, ekonomik kar ve performans oranı gibi performans göstergeleri üzerindeki etkisini araştırmak için parametrik çalışmalar yapılmıştır. Son olarak, belli çalışma koşulları altında, ekserji yıkımını azaltan ve artan net iş çıkışı nedeniyle ekonomik karı artıran termal mimari tespit edilmiştir. Bu çalışmada analiz edilen vakalarda, Senaryo - 4 (yani termal yapı 4), termodinamik ve pratik sınırlar içinde %69 ekserji verimliliği ile en iyi sistem performansını göstermektedir.
Anahtar Kelimeler: Organik Rankine çevrimi, Atık ısı geri kazanımı, Baca gazı, Enerji analizi, Ekserji analizi.

NOMENCLATURE

e	specific exergy (kJ/kg)
$\dot{E}$	exergy rate (kW)
h	specific enthalpy (kJ/kg)
H	enthalpy (kJ)
$\dot{I}$	exergy destruction (kW)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (kPa)
PC	percentage ratio (%)
PR	performance ratio (%)
Q	the heat transfer rate (kW)
s	specific entropy (kJ/kgK)
T	temperature (°C or K)
W	work (kW)
η	efficiency (%)

Subscription

o	dead state conditions
II	second law
evap	evaporator
hex	heat exchanger
in	inlet
out	outlet
OF	organic fluid

Superscript

quantity per unit time

INTRODUCTION

Due to increased energy consumption and rapid industrialization, mankind is faced with negative environmental and economic effects. In order to meet future energy demand while reducing greenhouse gas emissions and dependence on fossil fuels, development of energy production and/or conversion systems is unavoidable. A tremendous amount of heat is wasted. Forman et al. (2016) stated that 72% of the primary energy consumption is dissipated and 63% of the considered waste heat streams have temperature below 100°C (Forman et al., 2016). However, conventional energy production/conversion systems are not suitable for efficient production/conversion of low to medium grade heat sources. The Organic Rankine Cycle (ORC), which is a heat recovery technology, converts waste heat into power, using a low-boiling organic material as the working-fluid. The advantages such as adoptability to different operation conditions, construction simplicity, equipment sizes, automatic control and power generation ability make Organic Rankine Cycle (ORC) technology an ideal choice for heat and/or power production from low to medium temperature waste heat sources (Velez et al., 2012; Quoilin et al., 2013; Sun et al., 2017).

To guide the future researches, many review articles covering different aspects of ORC systems have been published (Chen et al., 2010; Tchanche et al., 2011; Bao and Zhao, 2013; Fu et al., 2014; Imran et al., 2018; Garcia et al., 2018). An important feature of ORC, which proposed by different authors, is the possibility of using different low grade heat sources and temperature ranges for power generation such as geothermal energy (Heberle and Brüggemann, 2010; El-Emam and Dincer, 2013), solar (Delgado-Torres and Garcia-Rodriguez, 2010), biomass (Al-Sulaiman et al., 2012), industrial waste heat (Etemoglu, 2013). So, the ORC systems emerge as a promising and powerful technique for the conversion of low to medium temperature heat sources (Tchanche et al., 2014; Zhai et al., 2016).

Organic working fluids significantly affect the efficiency of ORC systems, so selection of appropriate working fluids is important for system performance (Agromayor and Nord, 2017; Gyorke et al., 2018). According to Cengel (2007), a process with a lower entropy generation or higher second-law efficiency requires less energy input for a specified output (Cengel, 2007). Therefore, such a process conserves energy and energy resources. For this reason, the performance of the Organic Rankine cycle was analysed by many researchers from the perspective of energy conversion and exergy destruction theoretically (Mago et al., 2008; Safarian and Aramoun, 2015; Braimakis and Karellas, 2018) and experimentally (Fu et al., 2015).

Research on ORC systems is very active because it provides more efficient energy utilization for the needs of specific operating conditions. Some of these studies have concentrated on the new cycle designs and optimization of the system performance, which was committed to maximising the efficiency. Panesar et al. (2017) presented a heat recovery and working fluid test-rig to investigate a wide range of realistic gaseous sources such as the direct utilization of the High-Temperature (HT) exhaust gases. Optimal integration of ORCs with industrial processes is still a challenging task. To get optimal thermal architecture, operating conditions, and working fluids, an optimization technique was presented by Kermani et al. (2018).

Among these researches in the literature, investigations of the alternative thermodynamic cycles for ORC systems are essential in order to assure the cost-effective and optimal operation scheme. In this work, a parametric investigation is conducted to determine the effects of parameters which affect the performance of ORC-based combined cycles (FGA-ORCs) driven by flue-gas of stenter-frames. For this, five different thermal architectures, which is the novel aspect of the study, have been examined to show the direction for improvement possibility of FGA-ORCs. Furthermore, the present study describes an easy-to-follow procedure for calculation of the performance and exergy destruction of FGA-ORCs by an appropriate mathematical model which is based on the first and second-law of thermodynamics. Finally, the investigated five different cycles are compared in terms of economic profit, net power output and appropriate operating conditions.

THEORETICAL ANALYSIS

Stenter-frames are continuous dryers which are highly used in textile finishing operations. At the end of the mentioned textile process, the high volume of flue-gas is discharged into the environment. So, low-temperature flue-gas, which is suitable to recovery, is considered as a candidate for a new energy source.

The work potential of the energy contained in a system at a specified state is simply the maximum useful work that can be obtained from the system. This situation is described with the exergy term. Exergy represents quantitatively the useful energy, or the ability to do or receive work-the work content-of the great variety of streams (mass, heat, work etc.) that flow through the system (Cengel and Boles, 1989; Cengel et al., 2002; Bejan, 2002). So, the exergy analysis is a powerful tool for the design, analysis and classification of thermal systems. Disregarding kinetic and potential energy changes, the specific flow exergy of fluid at any state, e, can be calculated from Eq. (1).

$$e = h - h_o - T_o(s - s_o) \tag{1}$$

where h is the specific enthalpy (kJ/kg), s is the specific entropy (kJ/kgK), T is the temperature (K) and o is the dead state conditions. Multiplying specific exergy,e,by the mass flow rate of the fluid, $\dot{m}$, gives the exergy rate, $\dot{E}$, as

$$\dot{E} = \dot{m}e \tag{2}$$

The rate form of the entropy balance can be expressed by

$$\underbrace{\dot{S}_{in} - \dot{S}_{out}}_{Net\ entropy\ transfer\ rate} = \underbrace{\dot{S}_{gen}}_{Entropy\ generation\ rate} \tag{3}$$

and the entropy generation rate, $\dot{S}_{gen}$, for a steady-flow process can be calculated from the following equation:

$$\dot{S}_{gen} = \sum \dot{m}_{out} s_{out} - \sum \dot{m}_{in} s_{in} - \sum \frac{\dot{Q}}{T} \tag{4}$$

where $\dot{Q}$ is the heat transfer rate. Rate of exergy destruction (or the rate of irreversibility), $\dot{I}$, can be obtained based on the general exergy rate balance for steady-state open system could be expressed by means of the following equation:

$$\dot{I} = T_0 \dot{S}_{gen} \tag{5}$$

where T_0 is the temperature of dead state. The total exergy destruction, $\dot{I}_{TOTAL}$, of the system is calculated that the sum of the exergy destructions of each system components and the performance ratio of i_{th} device of the system, PR_i ,

$$PR_i = \dot{I}_i / \dot{I}_{TOTAL} \tag{6}$$

The schematic illustrations of the investigated FGA-ORC systems (i.e. investigated scenarios) can be seen in Figure 1.

Compared to a simple ORC system, five thermal architectures were designed to improve the net-work output of FGA-ORC systems. In the first thermal architecture (see Figure 1a), the effects of the turbine-to-heater mass flow rate and the internal heat exchanger on the system performance parameters were investigated. In the second thermal architecture shown in Figure 1b, the internal heat exchanger was used to improve the evaporator inlet conditions. In Figure 1c, before the turbine, a certain amount of organic fluid was separated from the main flow direction of the cycle and sent directly to the heat exchanger. Thus, the system efficiency was improved by increasing the temperature of the organic fluid entering the evaporator. A complex thermal architecture was shown in Figure 1d for better system efficiency. Having two turbines in the cycle provides a primary advantage for net-work output for the designed thermal architecture. Furthermore, the hot organic fluid from the throttling valve I improves the turbine II inlet conditions with the positive effect of the mixing chamber. Finally, the overall system efficiency was increased by increasing the temperature of the organic fluid entering the evaporator with the heat exchanger and pre-heater. The fifth thermal architecture has an internal heat exchanger and the mixing chamber before evaporator (see Figure 1e). At the turbine outlet, some amount of organic fluid was sent directly to the heat exchanger and then combined with the organic fluid from the condenser by the mixing chamber. Due to the change in the T-s diagram in the fifth cycle, a definite improvement in ORC system parameters was expected.

Second law efficiency, η_{II} (or exergetic efficiency) is expressed as the ratio of the performance of a device to the performance under reversible conditions for the same final states.

$$\eta_{II} = \eta / \eta_{rev} \tag{7}$$

where η is the actual thermal efficiency of FGA-ORC and η_{rev} is the maximum possible thermal efficiency at same conditions. Heat transfer rate and/or work-output can be easily calculated for steady-flow engineering devices such as turbine, pump, evaporator, condenser, throttling valve, mixing chamber and heat exchanger based on the first law of thermodynamics. For i_{th} device of the system,

$$\dot{Q}_i - \dot{W}_i = \sum H_{i,outlet} - \sum H_{i,inlet} \tag{8}$$

and

$$\sum \dot{m}_{i,inlet} = \sum \dot{m}_{i,outlet} \tag{9}$$

Economical profit of the FGA-ORC can be expressed as the sum of the price of the equivalent natural-gas rate to the recovered, if any, heat transfer and the produced electricity in the system. The price of natural-gas and electricity were taken as 0.2194 $/m^3 and 0.0664 $/kWh respectively.

The following several assumptions are adopted for the first and second law analyses of FGA-ORC (Safarian and Aramoun, 2015; Sun et al., 2017; Braimakis and Karellas, 2018).

1. All processes are steady state and steady flow with negligible potential and kinetic energy effects and no chemical or nuclear reactions.
2. The directions of heat transfer to the system and work output from the system are positive.
3. The turbine operation has an adiabatic efficiency of 80%.
4. Adiabatic efficiencies of the circulating pumps are 85%.
5. Pressure drops are ignored.
6. Outlet temperature of the condenser is 25°C and the quality is 0.
7. The dead state condition is taken as To=20°C and Po=100

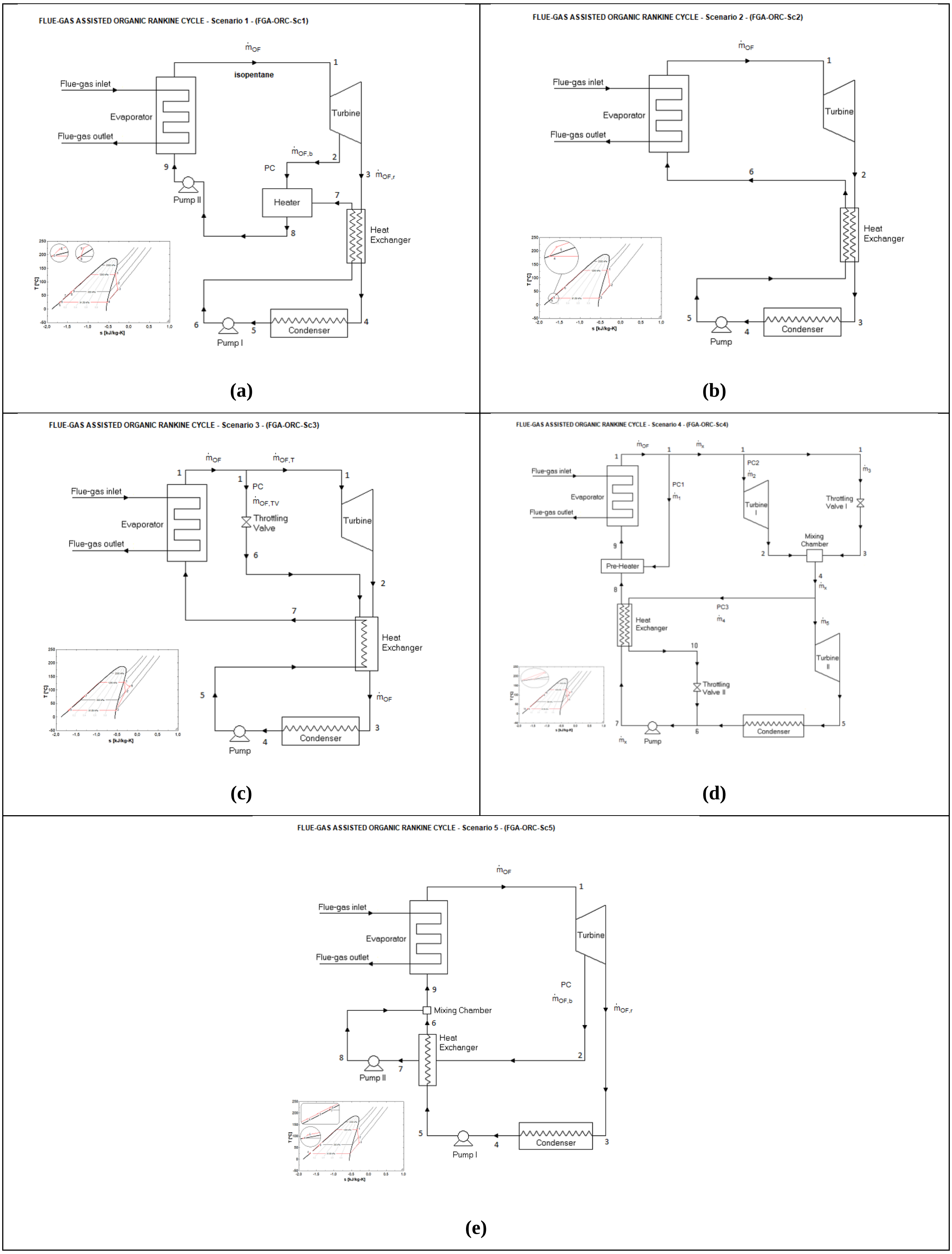


Figure 1. Schematic illustrations of FGA-ORCs.

RESULTS AND DISCUSSION

The optimization process for each thermal architecture is based on our codes on Engineering Equation Solver, EES. Performance of FGA-ORCs strongly depends on the thermo-physical conditions of the heat source and organic working-fluid. Among a lot of options, it may be challenging to find suitable working conditions for a specified waste-heat source, i.e. stenter-frame flue-gas, to maximize the efficiency and economic profit. So, the present study can be used to predict the effects of many parameters such as temperature, pressure, mass flow rate and dead state conditions on the performance of FGA-ORCs.

Characteristics of the examined heat source, flue-gas, are as follows: Volumetric flow rate was 20000 m^3/h and inlet temperature was 140°C. These values are the typical results of flue-gas measurement of a stenter-frame drying process.

The working-fluid of ORC should satisfy several criteria, such as environmentally friendly, safe, non-corrosive, low-cost, compatible for material contact, stability for certain temperature and pressure values. Moreover, critical point, latent heat, density, specific heat, curve of T-s diagram should also be considered for the selection of suitable working-fluid for ORC systems. So, isopentane was selected as the working fluid of the FGA-ORC because of its thermodynamics performance (Etemoglu, 2013). Table 1 summarizes the thermophysical properties of isopentane (Jang and Lee, 2018).

The evaporator capacity i.e. heat transfer rate from source to working fluid was kept constant as 255.6 kW for all the analysis for investigated thermal architectures. For this reason, the mass flow rate was recalculated for each different scenarios from the energy balance of the evaporator. Turbine inlet pressure and turbine inlet temperature were selected as 1250 kPa and $T_{turbine,inlet}=T_1=T_{gas,in}-10°C$, respectively.

Comparison of Thermal Architectures

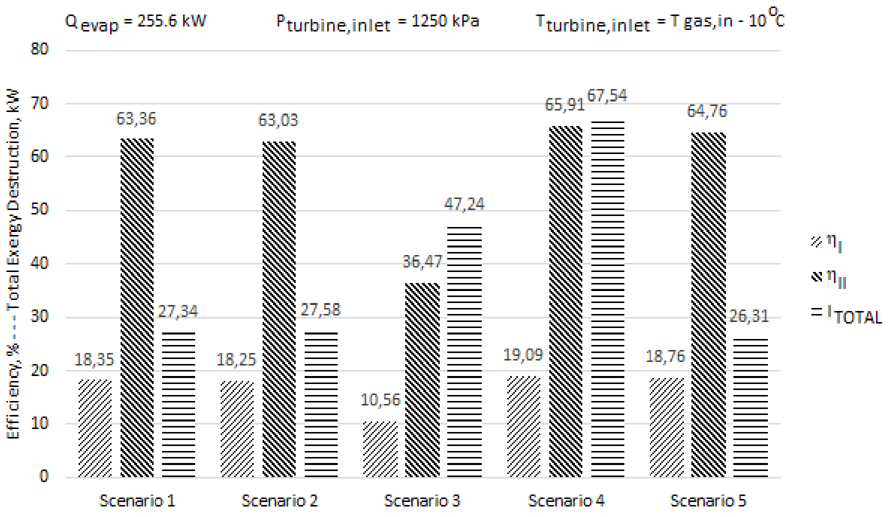
The most important stage for calculation of the system efficiency is definitely the correct choice of both working organic fluid and cycle thermal architecture. Making the wrong choice entails a poor cycle performance. Figures 2, 3 and 4 are presented to compare different scenarios (i.e. different FGA-ORCs). Figure 2 shows the comparison of thermal efficiency, η_I , exergy efficiency, η_{II} , total exergy destruction, $\dot{I}_{TOTAL}$, and economical value of equivalence electricity, $Profit_E$, of the different FGA-ORC systems. It is clearly observed from Figure 2 that Scenario 4 is more effective and more exergetic than the other scenarios for low pressure and temperature values.

Figure 3 also shows another comparison for different FGA-ORCs to determine the performance of main equipments such as evaporator, turbine, condenser. The relation between the thermal architecture of the cycle and the main system equipments can be easily seen from Figure 3. For example, in Scenario-1, 45% of the total exergy destruction is in the evaporator, while in Scenario-4 this value is about 11%. Thus, it is possible to determine the FGA-ORCs system equipments that needs to be improved for a given thermal architecture.

Table 1. Thermophysical properties and some characteristics of isopentane.

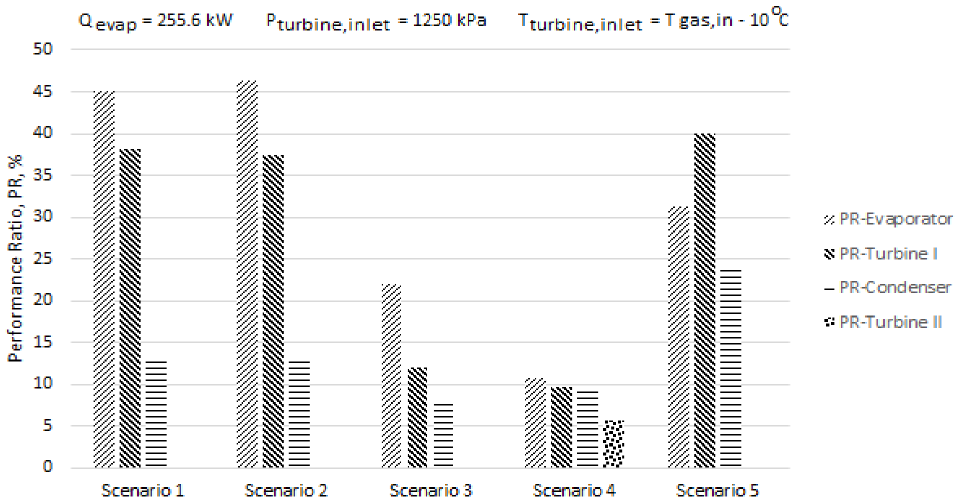
Fluid Type	Dry
Molecular Weight (g/mol)	72.1
$T_{boiling}$ (°C)	27.82
$T_{critical}$ (°C)	187.2
$P_{critical}$ (kPa)	3378
GWP	5
ODP	0

GWP : Global warming potential
ODP : Ozone depletion potential



	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
$\dot{m}_{OF}$, kg/s	0,6161	0,6062	0,6632	0,7931	0,7447
$Profit_E$, \$/h	3,115	3,099	1,793	3,24	3,184

Figure 2. Comparison of different scenarios.



	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
I-Evaporator, kW	12,33	12,8	10,43	7,33	8,215
I-Turbine I, kW	10,42	10,36	5,724	6,574	10,52
I-Condenser, kW	3,491	3,505	3,834	6,37	6,387
I-Turbine II, kW	-	-	-	3,81	-

Figure 3. Exergy destruction and performance rates for main equipments of different scenarios.

Figure 4 shows the effect of turbine (turbine-I for Scenario-4) inlet pressure on the thermal and exergetic efficiencies for different FGA-ORCs while the operation conditions was kept constant. It was observed that the highest efficiency values were obtained in Scenario-4 for investigated turbine inlet pressure values. It should be noted that the exergy destruction rates should be a positive quantity (I>0) for any actual thermal processes and that is valid for all the equipments of the thermal architectures of FGA-ORCs. As the exergy destruction rate of the heat exchangers in Scenario-1 and Scenario-2 were negative, these cycles could not be operated at P=3000 kPa due to the thermodynamic principles.

The various selection of thermal architectures is usually investigated with a search method type approach to limit the number of discontinuities in the objective function and to obtain more reliable results. This exhaustive approach is the strategy used in the researches about ORC applications. Technical limits, thermodynamic constraints and environmental and safety issues should be taken into account to exclude some thermal architectures or to fix some design parameters of ORCs. Therefore, the optimization process is carried out by examining the operating parameters of ORCs.

Optimization with Working Parameters for Best Thermal Architecture

Astolfi et al. (2017) stated that, the objective function for an optimization problem is the figure that is maximized or minimized during the optimization process. Therefore, for ORCs, two main classes of objective functions could be defined. (1) Maximizing the plant performance or (2) Minimizing the cost of the produced electrical power.

The search-method-type optimization process, which is performed step by step depending on the operating parameters, was presented to obtain maximum efficiency. The search methods generally fall into two categories, elimination, and hill-climbing techniques. In both, there is a progressive improvement throughout the course of the search (Stoecker, 1989).

Figures 2, 3 and 4 were used to identify the best thermal architecture that the research should focus on to determine the optimum operating conditions. For all the next cases in the present work, Scenario-4 which has the best thermodynamic performance was selected and investigated as the thermal architecture for FGA-ORC. In other words, Scenario-4 provides the highest thermal efficiency and exergetic efficiency in each case examined. Then, the optimization process in our study has been progressed step by step to find the best value of each parameter within the thermodynamic and practical limits for FGA-ORC.

Turbine-I inlet pressure

Figure 5 shows the effect of the turbine-I inlet pressure on the FGA-ORC performance indicators such as η_I, η_{II}, $\dot{I}$, and Profit$_E$. The highest thermal and exergetic efficiencies were calculated at 1311 kPa for investigated pressure range. Increasing the turbine-I inlet pressure from 800 kPa to 1311 kPa, within the thermodynamics limits, the total work output of the turbines increases by

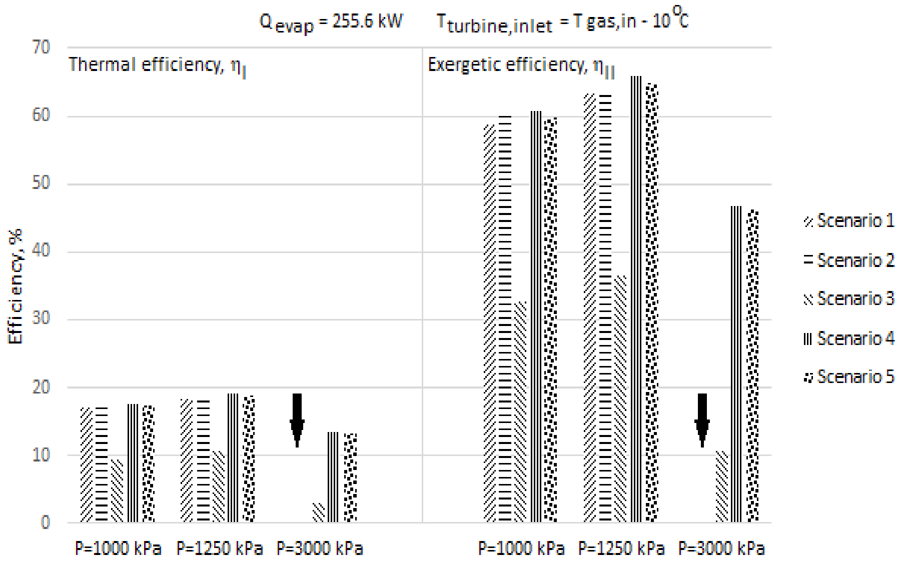
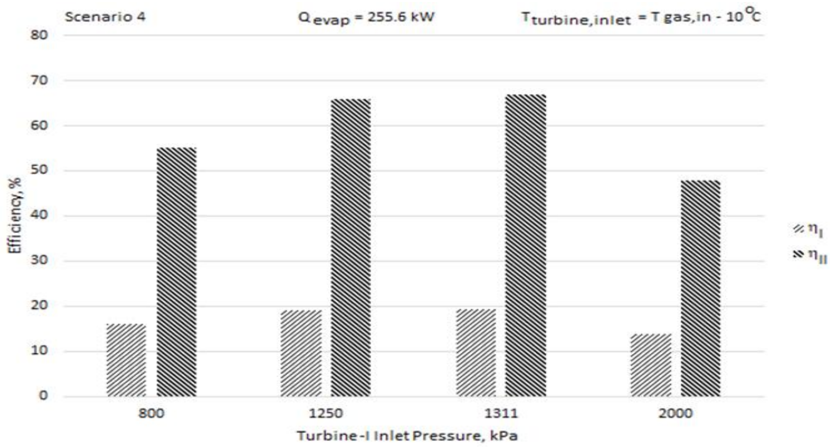


Figure 4. Efficiency values for different scenarios.



$\dot{m}_{OF}$, kg/s	0,7736	0,7931	0,7975	1,523
$Profit_E$, $/h	2,711	3,24	3,289	2,355
I-Evaporator, kW	15,74	7,33	6,541	19,72
I-Turbine I, kW	4,571	6,574	6,787	4,895
I-Condenser, kW	8,406	6,37	6,126	3,691
I-Turbine II, kW	3,733	3,81	3,829	4,527
PR-Evaporator, %	24,74	10,85	9,531	6,913
PR-Turbine I, %	7,184	9,733	9,888	1,716
PR-Condenser, %	13,21	9,432	8,925	1,294
PR-Turbine II, %	5,868	5,642	5,578	1,587

Figure 5. Effect of turbine-I inlet pressure for Scenario-4.

about 23% and the evaporator exergy destruction rate decreases by about 58%. At above 1311 kPa, mass flow rate and total exergy destruction rate of FGA-ORC increase and, as expected, thermal and exergetic efficiencies significantly decrease.

Turbine-I outlet pressure (i.e. cycle mid-pressure)

Turbine-I outlet pressure, i.e. cycle mid-pressure, is a significant factor affecting the efficiency of FGA-ORC. In order to predict the effect of outlet pressure of turbine-I on the efficiency values of FGA-ORC, the cycle mid-pressure values were varied from 200 kPa to 400 kPa (see Figure 6). The highest thermal and exergetic efficiencies were obtained when the turbine-I inlet pressure was 1311 kPa and the turbine-I outlet pressure was 300 kPa. As can be seen from Figure 6, FGA-ORC is not operated due to the exergy destruction value of the heat exchanger at low mid-pressures of the cycle, and moreover the efficiency values are decreased when the turbine-I inlet pressure was 2000 kPa.

Percentage ratio (PC)

The thermodynamic simulation developed in this study was designed in order to maximize the performance indicators such as η_I , η_{II} and $Profit_E$. Dependence of the investigated performance indicators on mass flow rate was also incorporated in the simulation. The magnitude of the performance indicators and exergy destruction rates clearly depend on mass flow rate through the components of FGA-ORC and characteristics of working fluids as well. Therefore, percentage ratio, PC, was defined to calculate the mass flow rate of the next component of the cycle, i.e. $\dot{m}_4 = PC3 \ x \ \dot{m}_x$ (see Figure 1-d).

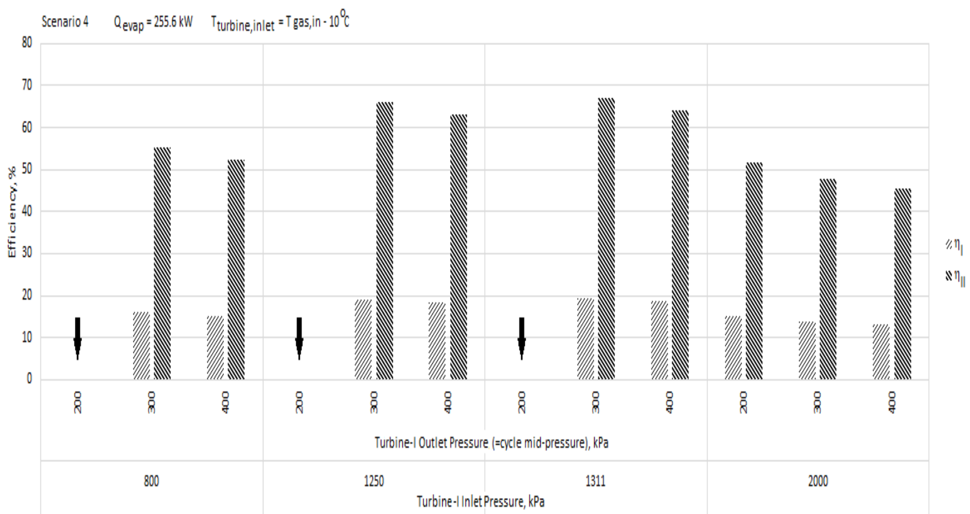
In Figure 7, the comparison of the effect of the mass flow rate percentage of the organic fluid which sent to the heat exchanger was shown based on data obtained from the present thermodynamic analysis. Increasing of PC3 from 30% to 38%, within the practical limits, the total exergy destruction rate decreases about 5% and, as expected, efficiency and profit values increase about 6.4%. Moreover, at same PC3 value range, it was also calculated that the heat exchanger capacity was increased by 41%. So, optimised FGA-ORC processes mean not only higher profits but also more efficient process in terms of lower environmental impacts.

Temperature difference (ΔT)

ΔT is the difference between the flue-gas inlet temperature of the evaporator and the turbine-I inlet temperature of the organic fluid. Plots of the exergy destruction rate and efficiency values versus ΔT are shown in Figure 8. It can be seen from Figure 8 that the total exergy destruction rate is increased by increasing ΔT, and, the efficiency values are decreased as expected. Exergy is consumed during the process due to irreversibilities, so, the increased ΔT is proved to produce bigger exergy destruction. It was also concluded that, in general, the exergy destruction rate of the evaporator was higher than those of the exergy destruction rates of the other components of FGA-ORC due to thermodynamics conditions.

Dead-state temperature

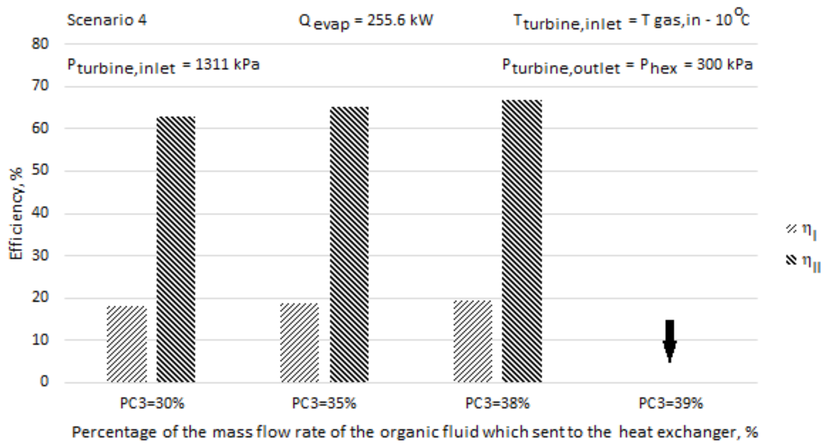
The dead-state is a state in which the system is equilibrium with its surroundings. Maximum possible work of a system at a specified state depends on dead-state conditions as well as the thermo-physical properties of the system. In other words, exergy is a property of the combination of the system and its surroundings. So, the calculated performance indicators of FGA-ORC as the results of energy and exergy analyses are sensitive to variations above mentioned properties. With the increase of dead state temperature, results obtained from the analysis represent that the exergy destruction rate decreases and the exergetic efficiency increases (see Figure 9). But, thermodynamic limits should always be considered, because Scenario-4 cannot be operated over the dead-state temperature of 29°C due to $I_{condenser}$<0.



$\dot{m}_{OF}$, kg/s	0,7624	0,7736	0,7817	0,782	0,7931	0,8012	0,7864	0,7975	0,8056	1,503	1,523	1,537
Profit, $/h	-	2,711	2,565	-	3,24	3,106	-	3,289	3,156	2,543	2,355	2,228
I-hex, kW	< 0	0,2192	2,867	< 0	0,09063	2,717	< 0	0,08866	2,716	0,1416	4,036	6,534
PR-hex, %	NA	0,3445	4,273	NA	0,1342	3,826	NA	0,1292	3,767	0,05098	1,415	2,249

hex : heat exchanger
NA : not available

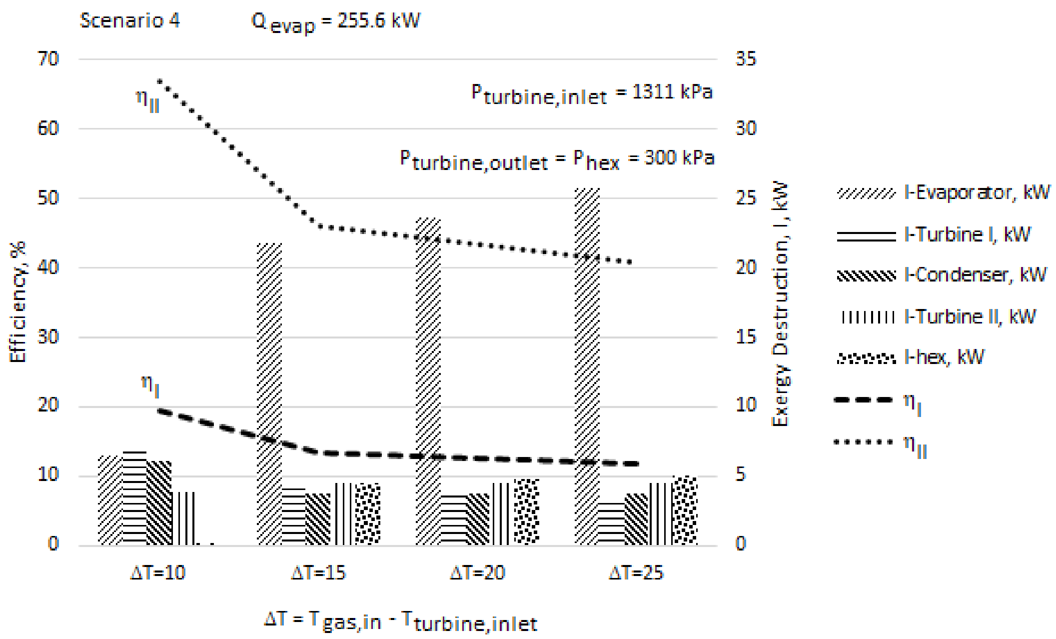
Figure 6. Effect of turbine-I outlet pressure for Scenario-4.



$\dot{m}_{OF}$, kg/s	0,7165	0,7651	0,7975	0,8089
Profit, $/h	3,092	3,211	3,289	-
I-hex, kW	1,87	0,9021	0,08866	< 0
PR-hex, %	2,589	1,287	0,1292	NA

hex : heat exchanger
NA : not available

Figure 7. Effect of PC3 on performance parameters for Scenario-4.



$\dot{m}_{OF}$, kg/s	0,7975	1,605	1,708	1,823
Profit, $/h	3,289	2,263	2,133	2,003
I-TOTAL, kW	68,64	310	341	375,6

Figure 8. Effect of ΔT on performance parameters for Scenario-4.

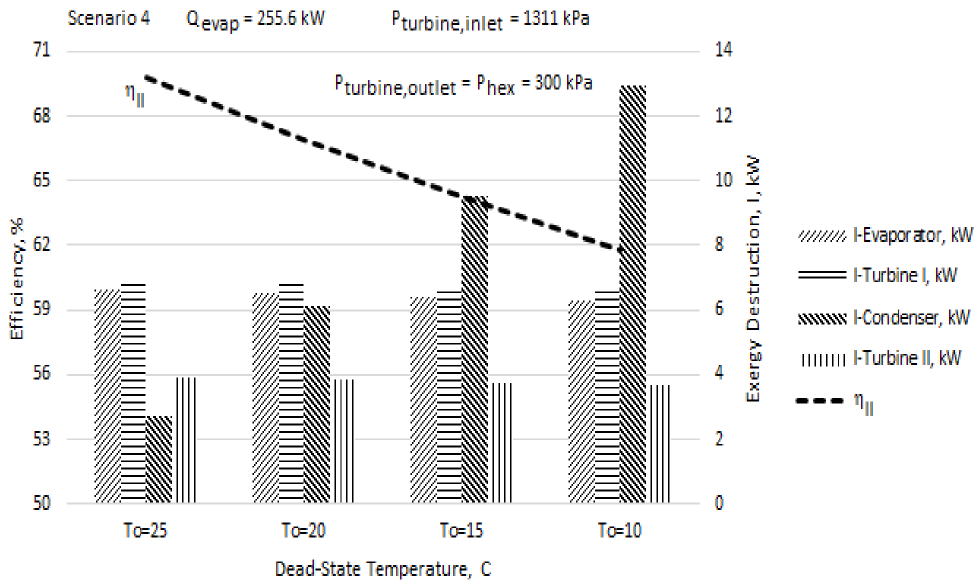
CONCLUSIONS

Due to the facts of high production costs of the primary energy production as well as more and more stringent environmental legislation, the waste-heat recovery is expected to gain increasing importance depending on the global sustainable development goals. The design and optimization process for a generic ORC has three different stages: (1) analysis of the problem, (2) working fluid and cycle configuration selection, and (3) system optimization. In this study, a systematic roadmap with the steps mentioned above was presented for academic and industrial users.

ORCs are promising technology that is feasible and economical while minimizing the risk to human health and the environment. Energy and exergy based thermodynamics analysis were carried out for FGA-ORCs to provide a better guidance for system improvement. And, in this study, to assure high flexibility and efficiency for waste-heat recovery from low to medium grade heat sources, five different thermal architectures were investigated using isopentane as organic fluid. Based on the present analysis, the following results are concluded:

1. Exergetic optimization is a useful method for determining the optimal design of different thermal architectures for given thermodynamic constraints. So, the results of the analysis show that optimum values of pressure, temperature and mass flow rate can be obtained for different FGA-ORCs.

2. The presented thermodynamic analysis is a powerful tool for the evaluation of thermal system performance. For analyzed cases in this study, Scenario-4 shows the best system performance by an exergy point of view. From the results of the analysis for Scenario-4, the maximum value of the exergetic efficiency is found to be 69% at P_1=1311 kPa, P_4=300 kPa, ΔT=10°C, PC3=38%, To=25°C.



I-TOTAL, kW	66,29	68,64	70,98	73,33

Figure 9. Evaluation of the effect of dead-state temperature for Scenario-4.

3. Organic fluid mass flow rate which sent to heat exchanger from turbine-I, and, the mid-pressure of the cycle should not be underestimated in the performance calculations of Scenario-4. As can be seen from the results of the analyses, depending on thermodynamic principles and the concept of exergy destruction, the maximum results for FGA-ORC efficiency could be provided by the optimum values of the mentioned parameters.

4. While the total exergy destruction decreases, the turbine work-output and economic profit increase, in general. Finally, obtained results represent that the decrease of the total exergy destruction rate with the increase of dead state temperature.

In order to avoid serious environmental and economic threats, the written reports of the Intergovernmental Panel on Climate Change (IPCC) have strongly recommended that the increase in global temperature should be limited. So, ORC systems will contribute to reducing the carbon footprint and waste energy in industrial facilities in accordance with the above recommendation. Thus, it is hoped that the results obtained in this study would be provided a better understanding of optimal control and operation strategy for FGA-ORCs with constant evaporator capacity.

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