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Exergy analysis of orc integrated combined cycle power plant with single pressure heat recovery steam generator

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Abstract

There is energy crises in world so increasing demand of power has made the power plants of scientific interest, but most of the power plants are designed by the energetic performance criteria based on first law of thermodynamics only. The real useful energy loss cannot be justified by the fist law of thermodynamics, because it does not differentiate between the quality and quantity of energy. The exergy analysis (second law analysis) is used for providing information about the losses qualitatively as well as quantitatively along with their locations. Exergetic optimization improves the performance of a system by reducing the exergy destruction and increasing exergetic efficiency. This analysis shows exergy loss at each and every point of unit equipment's. Also presents major losses of available energy at combustor, HRSG and gas turbine and organic condenser. The primary objectives of this work are to analyze the system components separately and to identify and quantify the sites having largest exergy losses at different load. Exergy analysis considered real variation ranges of the main operating parameters such as pressure ratio, air fuel ratio. The effects of theses parameters on the system performances are investigated.

Keywords: combined cycle, organic Rankine cycle, heat recovery steam generator, exergy analysis, gas turbine.

1. Introduction

Energy systems contain an extremely large number and a few types of coordinated efforts with the world outside their physical limitations. Thus, architects must address numerous wide issues, particularly energy, economy and the environment. Combined cycle power plants (CCPPs) have as of late gotten significant consideration because of their nearly high energy efficiencies, low poisonous waste and ozone depleting substance releases, and operational suppleness. A typical combined cycle power plant is the cycle, which is comprised of a gas cycle (topping cycle) and a steam turbine cycle (bottoming cycle) coupled through a heat recovery steam generator (HRSG).But exhaust gas from the gas turbine is not fully utilized by the HRSG. Almost 150^0 C goes to waste from HRSG with exhaust through stack. This low amount heat can be fully utilize with the low temperature heat cycle such as the integration of organic Rankine cycle (bottom left cycle).In this organic Rankine cycle first law analysis is not sufficient for telling about performance of the cycle because some critical components have more exergy destruction in this cycle such as organic condenser, heat recovery boiler (HRB).

To streamline the efficiency, cost viability and ecological effect of such plants, it is critical to decide the areas, sorts and genuine extents of wasteful aspects (irreversibility's). Exergy investigation is a helpful tool for such examinations, and allows measurement of the thermodynamic wasteful aspects of the procedure.

The scope and purpose of this research is to develop effective methodology to achieve exergetic optimizations of CCGT power plants. Therefore, the aim of the work is to improve the performance of the power plant by means of proposing an exergy optimization method. With the help of this method, it would be possible to

(a) Provide information about the exergy destruction and exergy losses along with their location.
(b) Predict the highest exergy destructor components of the system.
(c) Suggest ways of improving the exergetic efficiency.
(d) Find the optimal realistic values of operating parameters, which gives the maximum possible power output and efficiency. Additionally, is would be

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possible to calculate minimum possible exergy destructions.

2. Literature Review

In order to have an idea of the present methodology development in the area of performance and optimization of combined cycle gas turbine power plant, a brief survey of available literature was made. However, this chapter is concerned with a review of literature on optimization performed on various thermal systems. In general, some authors focus on the gas turbine operating parameters (topping cycle), others optimize the steam plant (bottoming cycle) on the basis of a given gas turbine, whereas others propose appropriate optimization methods for the whole combined cycle power plant. Furthermore, the optimization can be analyzed from a thermodynamic point of view, according to the first and/or second law analysis, or using a thermo economic or environmental-economic strategy Kaviri et al [1], Ahmadi and Dincer [2], Boyano et al [3] and Petrakopoulou et al [4]). From the point of view of optimization methodology, there are many types of analyses. In this work, the review will highlight most common methodology: the exergy destruction method, and the exergo economic method: Ibrahim et al [5], Ameri and Hejazi [6], Boonnasa et al [7] and Hosseini et al [8]. The properties of air entering combustion chamber depend upon the compressor pressure ratio studied by Ibrahim and Rahman [9], and Khaliq and Kaushik [10] performed a parametric thermodynamic analysis of a combined cycle gas turbine. They investigated the effect of operating parameters, compression ratio, gas-turbine peak temperature ratio, isentropic compressor and efficiency and air fuel ratio on the overall plant performance. Their results show that the compression ratios, air to fuel ratio as well as the isentropic efficiencies are strongly influenced by the overall thermal efficiency of the combined cycle gas turbine power plant. The overall thermal efficiency increases with compression ratio as well as isentropic compressor and turbine efficiency. However, the variation of overall thermal efficiency is minor at the lower compression ratio while it is very significant at the higher compression ratio for both isentropic compressor and turbine efficiency. The overall efficiencies for combined cycle gas turbine are much higher than the efficiencies of gas turbine plants power output decreases linearly with the increase temperature. Mohagheghi and Shayegan [11] performed the thermodynamic optimization of design variables and heat exchangers layout in a heat recovery steam generator HRSG for combined cycle gas turbine CCGT using a genetic algorithm. Their method was introduced for modeling the steam cycle in advanced combined cycles by organizing the non-linear equations and their simultaneous used solutions with numerical methods. 8 In addition to the optimization of design variables of the recovery boiler, they performed the distribution of heat exchangers among different sections and optimized their layouts in HRSGs. A standard gas turbine was assumed, and then outlet gas stream conditions (mass flow rate, temperature, and chemical composition of gas stream) were considered as the inlet parameters for the recovery boiler model. From the optimization process maximum output power from a steam cycle for different HRSGs was then analyzed.

Bracco and Silvia [12] studied a combined cycle power plant with a single level heat recovery steam generator HRSG. They developed a mathematical model to determine the optimal steam pressure values in the HRSG according to different objective functions (in the HRSG for a given gas turbine). Their work reports numerical results for the combined cycle power plant considering four different gas turbines. The optimization approach was focused on the study of the heat transfer between the steam and the exhaust gas in the HRSG, based on an exergetic analysis. They present the comparison among different objective functions that refer to the HRSG specifically or to the whole bottoming cycle. In their mathematical model, they considered the presence of specific constraints for the operating parameters of the power plant, the most important constraints that were considered refer to the steam quality at the turbine outlet, the HRSG outlet exhaust gas temperature and the steam turbine blade height. In their work, a parametric analysis was also performed to evaluate the influence of the gas temperature at the HRSG inlet and the pinch point temperature difference on the considered objective functions. Woudstra et al [13] performed the thermodynamic evaluation of combined cycle plants with the same gas turbine and different steam bottoming cycles. The evaluation showed that the increasing the number of pressure levels of steam generation will reduce the losses due to heat transfer in the HRSG, but also the exergy loss due to the exhaust of flue gas to the stack. Among the investigated configurations for bottoming cycle, triple pressure reheat was the best option from exergy point of view. Mansouri et al [14] investigated the effect of pressure levels of steam generation at heat recovery steam generator HRSG on the energetic and exergetic efficiency of HRSG, bottoming cycle and combined cycle power plants, as well as the effect of 9

Xiang and Chen [15] considered a combined cycle with three-pressure HRSG, equipped with the GE PG9351FA gas turbine. They maximized the combined cycle efficiency through the optimization of the HRSG operating parameters by minimizing exergy losses.

From the literature review it is found that the efficiency of the combined cycle is more than the simple individual cycle. Other important conclusion found that the more and more energy going to waste from stack with exhaust flue gases even after passing through HRSG. Almost flue gas around 150 ^{0}C is going to waste from stack. It is concluded that no researcher use the energy at temperature 150^{0}C from the flue gases and also not done exergy analysis of this model. The integration of the ORC (organic Rankine cycle) in the pre-existing cycle is done for recovery of the low temperature heat from the exhaust gases which are coming from the HRSG after generation of the steam for simple Rankine cycle and exergy analysis is carried out for whole system. It is proposed to examine the effect of the various parameters on the performance of the combined cycle with ORC. These parameters are following

- Effect of the pressure ratio
- Effect of the air fuel(A/F) ratio

3. Exergy Analysis

For thermodynamic analysis (exergetic and energetic) a model is proposed in this model there are following components-compressor, combustor, gas turbine ,steam turbine, HRSG, condenser, heat recovery boiler, organic turbine, pumps Which are shown in figure 1.

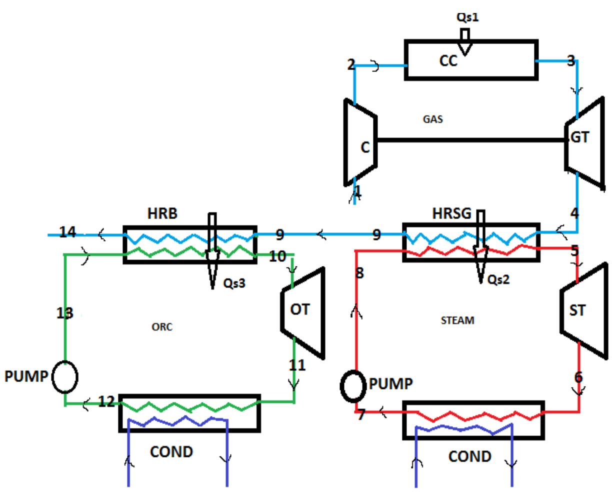

Figure 1: Thermodynamic model of combined cycle with ORC

3.1 System Description

Systems have the different components which are described above following ways it is works through following points

At stage 1 there is ambient conditions are defined this is the entry of the compressor and point 2 is the entry of the combustion chamber where heat is given and then combustion of fuel takes place. After the combustion is over the hot flue gases goes to the gas turbine at stage 3 where work is taken by rotation of the shaft .After expansion flue gases goes to the HRSG at stage 4 at pressure above the slightly above the atmospheric pressure where heat is given to the water for generation of the steam and remaining hot gases from stack goes to the heat recovery boiler at stage 9.stage 5 is entry to steam turbine and stage 6 exit to the steam turbine and entry to the surface condenser. In heat recovery boiler the heat is given to the organic fluid (R410A) which is circulates in ORC plant. At stage 10 organic fluid vapours goes to the organic expander where small amount of work is recovered. At stage 14 the remaining gases goes to atmosphere almost at atmospheric temperature and pressure. Then there is no potential remains. This is shown in figure 1.

Following assumptions are made in the study of this model:

1. All components are in steady state.
2. No pressure loss in any component.
3. There is no heat and pressure loss in pipes connecting in each components.
4. After steam turbine and organic expander fluids are saturated vapour.
5. No pressure loss in HRSG and heat recovery boiler

3.2 Exergy Analysis

Exergy destruction or loss is given by

$$\dot{E}D_i = \sum(\dot{m}e)_{in} - \sum(\dot{m}e)_{out} + \left[\sum\left(\dot{Q}(1-\frac{T_0}{T})\right)_{in} + \sum\left(\dot{Q}(1-\frac{T_0}{T})\right)_{out}\right] \pm \sum\dot{W}$$

Exergy destruction rate in compressor given

$$EDc = m_a*T_0*(s_2 - s_1)$$

Exergy destruction rate in combustion chamber given as

$$EDcc = (m_f+m_a)*T_0*(s_3-s_2)-Qs_{1*}(1-T_0/Tc)$$

Exergy transfer in combustion chamber from fuel is given as

$$ET = Q_{S1}*[1-T_0/T_C]$$

Exegy destruction rate in gas turbine given as

$$EDgt = (m_f+m_a)*T_0*(s_4-s_3)$$

Exergy destruction rate in HRSG given as

$$ED_{HRSG} = m_a*[(h_4-h_9)-T_0*(s_4-s_9)]+m_s*[(h_8-h_5)-T_0*(s_8-s_5)]$$

Exergy destruction rate in steam turbine given as

$$EDst = m_s*T_0*(s_6 - s_5)$$

Exergy destruction rate in steam condenser given as

$$EDcond= m_s*[(h_6-h_7)+T_0*(s_6-s_7)]$$

Exergy destruction rate in HRB given as

$$ED_{HRB} = (ma+mf)*[(h_9-h_{14})-T_0*(s_9-s_{14})]+m_{of}*[(h_{13}-h_{10})-T0*(s_{13}-s_{10})]$$

Exergy Destruction rate in organic turbine given as

$$EDot = m_{of}*T_0*(s_{11}-s_{10})$$

Exergy destruction rate in organic condenser given as

$$EDocond = m_{of}*[(h_{11}-h_{12})+ T_0*(s_{11}-s_{12})]$$

Overall exergetic efficiency of plant with ORC

$$\eta_{exergetic\ with\ ORC} = (W_{GT} +W_{ST} +W_{OT}–W_C – W_P-W_{OP}) /ET$$

4. Results and Discussions

The study of different cycles on which the thermal power plant work with respect to exergy. The exergy destruction shows a loss that can be recovered by using the suitable design of the various portions of the system and also it confirms the best possible process of the power plant according to second law of Thermodynamics. As the exergy and cost of energy are complimentary to each other exergy destruction shows a loss, which can be quantify by analysis the system in mathematically. In the present work the analysis is done in the combined cycle power plant. Fig.2 shows exergy destruction of air compressor as a function of air fuel ratio at various pressure ratios. Pressure ratio was varied from 5 to 20 while air fuel ratio was varied from 60 to 130. With the increase in air fuel ratio, exergy destruction rate of air compressor increases. Here, the mass of fuel remains constant as 1Kg and mass of air increases so air fuel ratio. To compress more air, compressor has to work more and it results in increased exergy destruction rate. At a particular ratio, as pressure ratio increases exergy destruction rate increases too. This is because more work required by compressor and work done required by compressor is directly proportional to the pressure ratio. Fig 3 demonstrates the variation of Exergy destruction rate of combustion chamber as a function of air fuel ratio at various pressure ratios. Air fuel ratio was varied from 60 to 130. Pressure ratio was varied from 5 to 20 in a step of 5. With the increase in air fuel ratio, the exergy destruction rate increases. This is due to the increased amount of heat addition in combustion chamber and it results in increment of exergy destruction rate. At a particular air fuel ratio, as pressure ratio increases the exergy destruction rate decreases. This happens because due to increased pressure ratio, combustion chamber receives the air with high temperature so it requires less chemical energy addition.

Fig 5 illustrates the variation of Exergy destruction rate of HRSG as a function of air fuel ratio at various pressure ratios. As air fuel ratios increasing, exergy destruction rate is increases very rapidly because at lower air fuel ratio, the inflow temperature is high and decreasing with increase in AFR those results increases destruction rate. At a particular inlet temperature, with increase in air fuel ratio the exergy destruction rate increases. This is due to the increased amount of heat addition in combustion chamber and it results in increment of exergy destruction rate. At a particular inlet temperature, as air fuel ratio increases, marginal exergy destruction rate decreases.

Fig 6 displays the Exergy Destruction Rate of steam turbine at Various Pressure Ratios versus Air Fuel Ratio. On increasing the pressure ratio, the temperatures increased is very much high as compared to temperature decreased by increasing air fuel ratio that's why exergy destruction rate continuously increases on increasing air fuel ratio and at higher pressure ratio.

Fig 7 indicates the Exergy Destruction Rate of condenser at Various Pressure Ratios versus Air Fuel Ratio. This shows the same pattern as of steam turbine and reason is same too.

Fig 8 displays exergy destruction in HRB with air fuel ratio at different pressure ratio. On increasing air fuel ratio exergy destruction increases because increases air fuel ratio more heat required in combustion chamber as discussed above so more inlet temperature in HRB.

Fig 9 shows the variation in exergy destruction with air fuel ratio in organic turbine. In this fig same reason as fig 9 for increasing exergy destruction. No effects on exergy destruction on pressure ratio because HRB inlet and outlet temperatures are fixed but it varies based on design of HRB. Also same reason and effects of air fuel ratio and pressure ratio on other component of ORC system. Input parameters taken for study are given below these parameters are taken from different running power plants. These are shown in Table-1

Table-1: Input parameters of Gas turbine power plant with ORC

S.No	Parameters	Symbol	Value
1	Ambient temperature	T_0	298K
2	Flue gases temperature from Flue gases temperature from HRSG.	T_9	423K
3	Constant pressure in HRSG	P_5	10 bar
4	Temperature inlet to steam turbine	T_5	813K
5	Temperature inlet to organic turbine	T_{10}	403K
6	Pressure inlet to organic turbine	P_{10}	25bar
7	Pressure outlet to organic turbine	P_{11}	2bar
8	Pressure outlet to steam turbine	P_6	0.07bar
9	Outlet temperature of gases from HRB	T_{14}	300K
10	Organic fluid for ORC	R410A	-

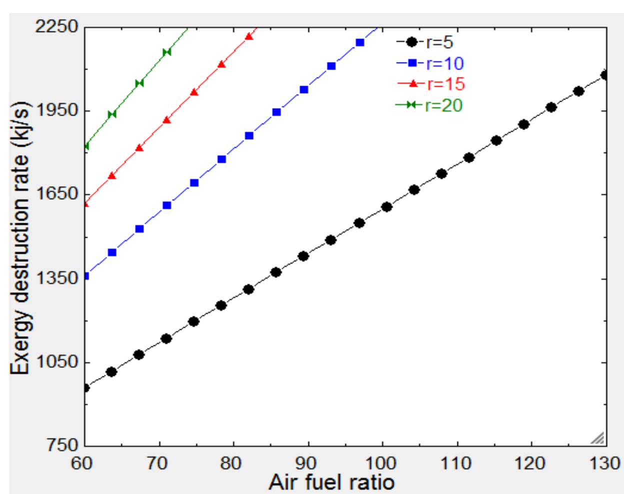

Figure 2: Variation of exergy destruction rate in compressor with air fuel ratio at different pressure ratio

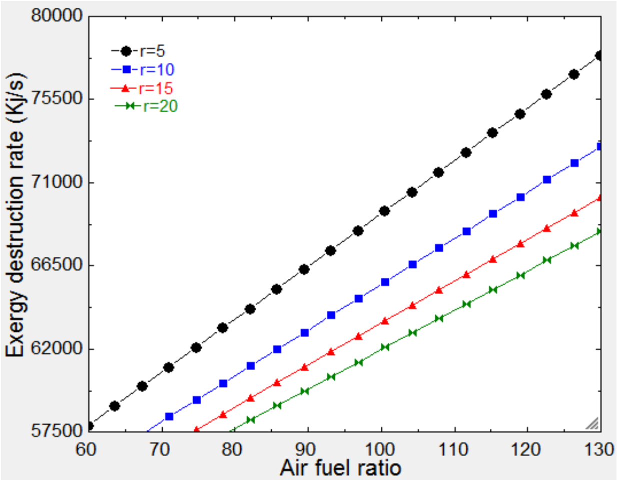

Figure 3: Variation of exergy destruction rate in combustion chamber with air fuel ratio at different pressure ratio

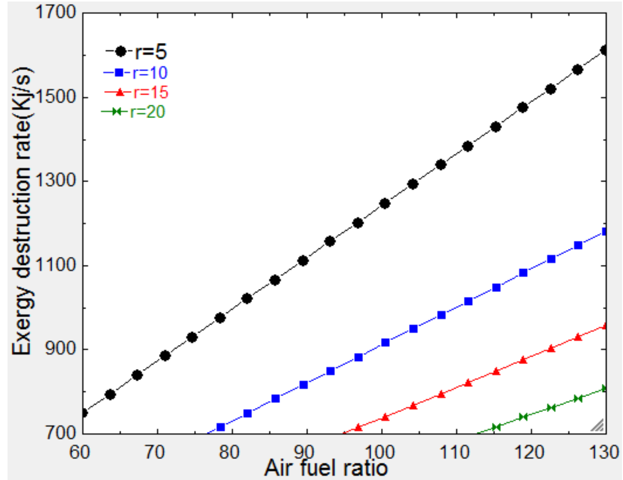

Figure 6: Variation in exergy destruction rate in steam turbine with air fuel ratio at different pressure ratio

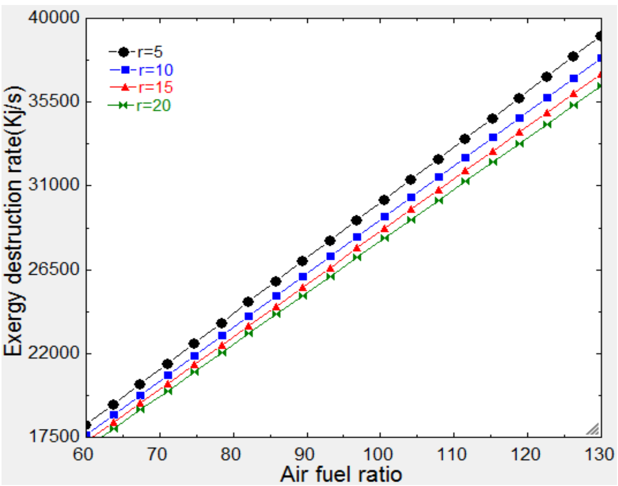

Figure 4: Variation of exergy destruction rate in gas turbine with air fuel ratio at different pressure ratio

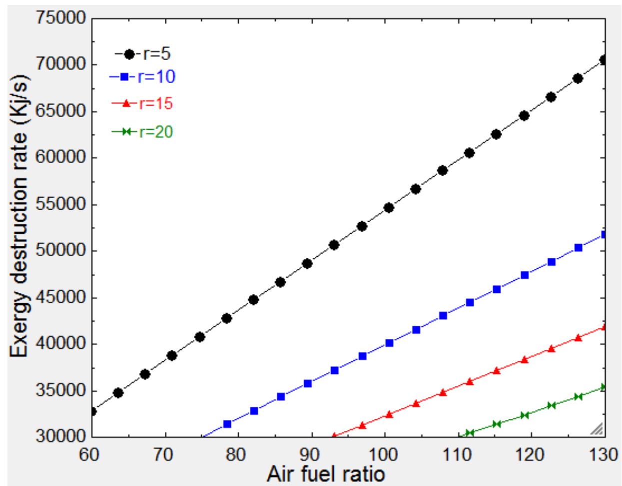

Fig 7: Variation in exergy destruction rate in steam condenser with air fuel ratio at different pressure ratio

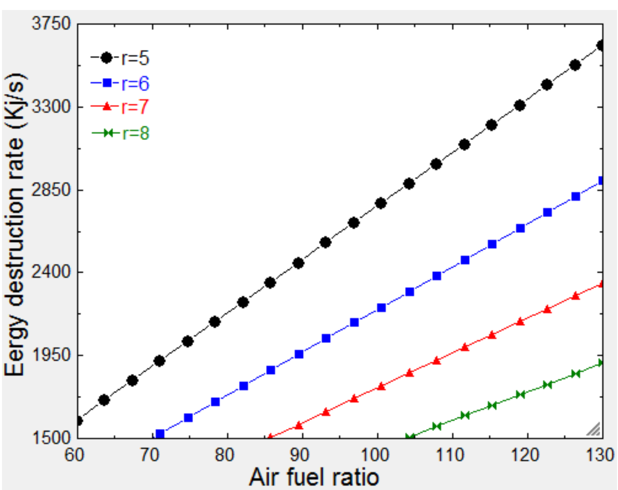

Figure 5: Variation in exergy destruction rate in HRSG with air fuel ratio at different pressure ratio

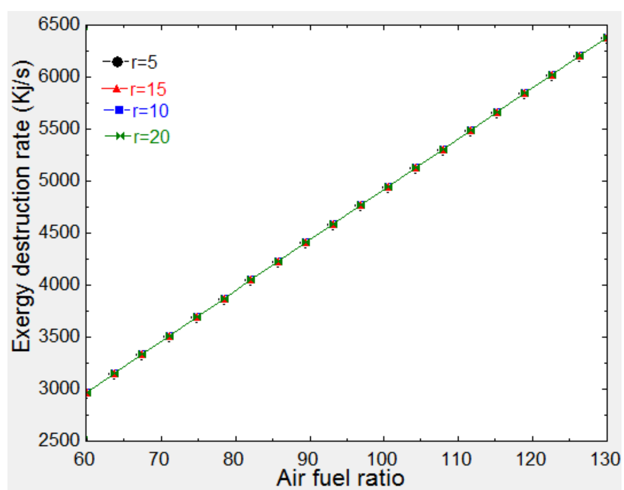

Figure 8: Variation in exergy destruction rate with HRB with air fuel ratio at different pressure ratio

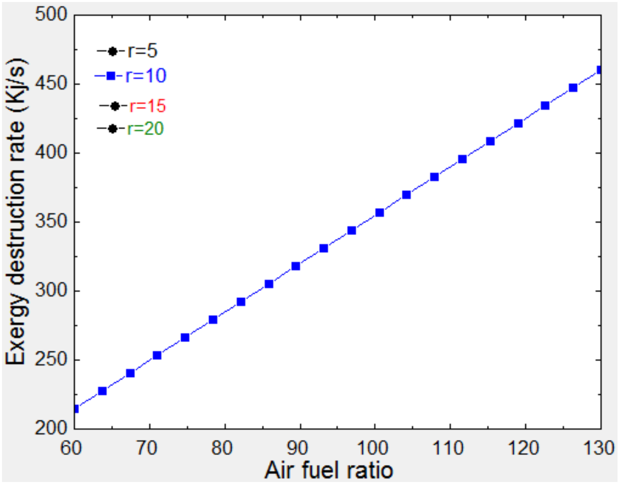

Figure 9: Variation in exergy destruction rate in organic turbine with air fuel ratio at different pressure ratio

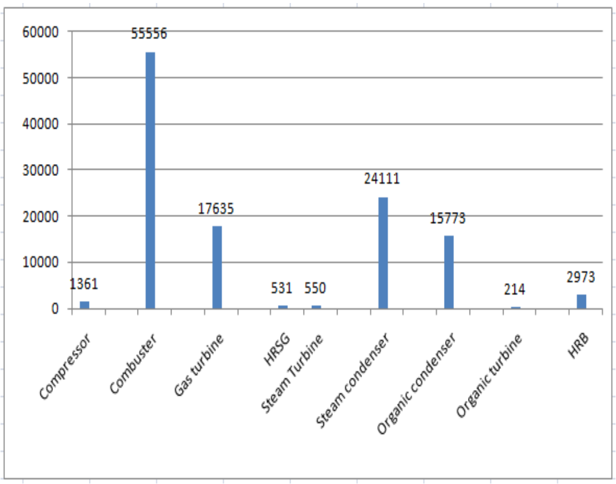

Figure 10: Exergy destruction rate (kj/s) for each component of system

The variation of thermodynamic performance parameter in terms of exergetic efficiency with pressure ratio are shown in fig. (11) and second law efficiency in terms of exergetic efficiency with air fuel ratio is shown in fig.(12). It is shown that exergetic efficiency is increasing continuously with pressure ratio but decreasing with air fuel ratio. This is because increasing pressure ratio compressor outlet temperature is increase responding exergy transfer decrease having same work output and hence exergetic efficiency increases. On other hand decrease in exergetic efficiency with increase in air fuel ratio, because increase in air fuel ratio decreases the inlet temperature of the gas turbine and also flue gases .so exergy transfer in combustor have to be increase.

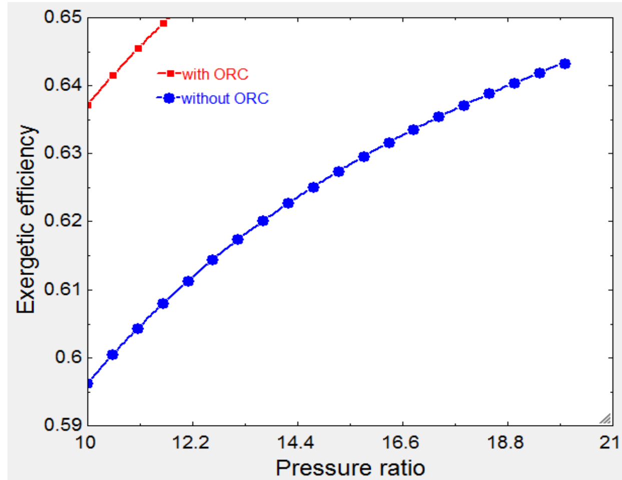

Figure 11: Variation of Exergetic efficiency with pressure ratio

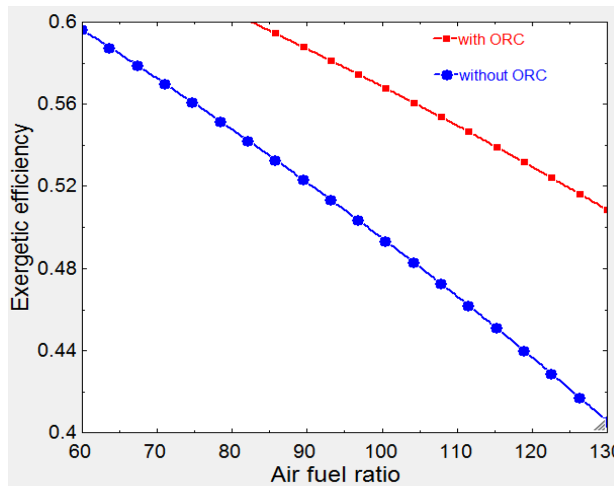

Figure 12: Variation of Exergetic efficiency with air fuel ratio

The variation of thermal efficiency (first law efficiency in terms of energy efficiency with respect to the pressure ratio of Combined cycle Gas turbine power plant with ORC and first law efficiency (thermal efficiency in terms of energy efficiency) with air fuel ratio respectively and compared efficiency with and without ORC shown in Fig-13 and Fig-14 respectively. .Same effects are calculated as well as exergetic efficiency without ORC. Here also same reason for increase and decrease of thermal efficiency (first law efficiency in terms of Energy Efficiency and second law efficiency in terms of exergetic efficiency with pressure ratio and air fuel ratio shown in Fig-13 & Fig-14 respectively .

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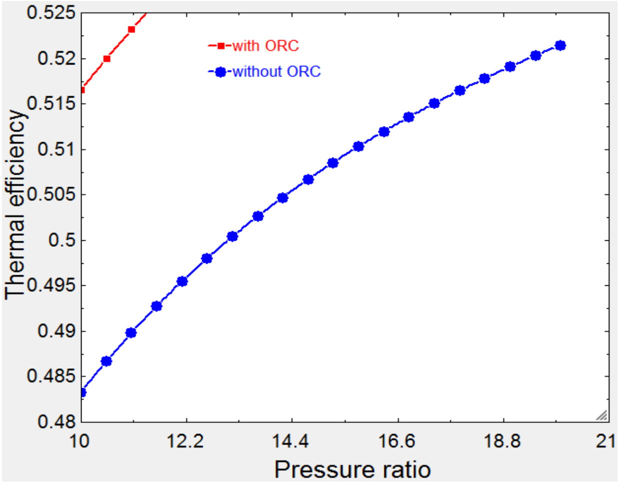

Figure 13: Figure 5: Thermal efficiency vs air fuel ratio pressure ratio

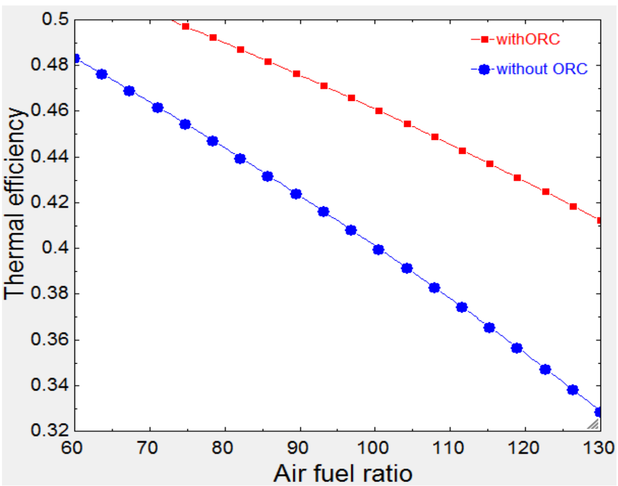

Figure 14: Variation of first law efficiency in terms of Thermal efficiency (Energy Efficiency) with air fuel ratio

5. Conclusions

Following conclusions have been made

1. Maximum exergy destruction components are combustor, gas turbine and steam condenser.
2. In organic Rankine cycle organic condenser and HRB have more exergy destruction.
3. More sensitive components are HRSG and HRB. So design of these required carefully.
4. Exergy destruction in each component in ORC with pressure ratio depends on design of HRB.
5. Combined cycle Gas turbine power plant with ORC, the second law efficiency in terms of exergetic efficiency is more than combined cycle Gas turbine power plant without ORC.
6. Combined cycle Gas turbine power plant With ORC, the thermal efficiency (in terms of first law efficiency) defined as energy efficiency is more than combined cycle Gas turbine power plant without ORC.
7. The integration of ORC with the existing combined cycle is effective and heat from the exhaust gases is fully utilized by integration of ORC.

References

[1] Kaviri A. G., Jaafar M. N., Lazim T. M., ikoij\Barzegaravval, H., Exergy environmental optimization of Heat Recovery Steam Generators in combined cycle power plant through energy and exergy analysis. Energy Conversion and Management, 6(2013), pp.27–33.

[2] Ahmadi P., Dincer I., Exergo environmental Analysis and Optimization of a Cogeneration Plant System using Multimodal Genetic Algorithm (MGA). Energy, 35(2010), pp. 5161-72.

[3] Boyano A., Blanco-Marigorta A. M., Morosuk T., Tsatsaronis G., Exergoenvironmental Analysis of a Steam Methane Reforming Process for Hydrogen Production. Energy, 36(2011), pp. 2202-2214.

[4] Petrakopoulou F., Boyano A., Cabrera M., Tsatsaronis G., Exergo economic and Exergo environmental Analyses of a Combined Cycle Power Plant with Chemical Looping Technology. International Journal of Greenhouse Gas Control, 5(2011), pp. 475-482.

[5] Ibrahim K. T., Rahman M. M., Abdalla N. A., Optimum Gas Turbine Configuration for Improving the Performance of Combined Cycle Power Plant. Procedia Engineering,15 (2011), pp.4216-4223.

[6] Ameri M., Hejazi H. S., The Study of Capacity Enhancement of the Chabahar Gas Turbine Installation using an Absorption Chiller. Applied Thermal Engineering, 24(2004), pp.59–68.

[7] Boonnasa S., Namprakai P., Muangnapoh T., Performance Improvement of the Combined Cycle Power Plant by Intake Air Cooling using an Absorption Chiller, Energy,31(2006), pp. 2036–2046.

[8] Hosseini R., BeshkanI. A., Soltani M., Performance Improvement of Gas Turbines of Fars (Iran) Combined Cycle Power Plant by Intake Air Cooling using a Media Evaporative Cooler. Energy Conversion and Management, 48(2007), pp. 1055–1064.

[9] Ibrahim T. K., Rahman M. M., Effect of Compression Ratio on Performance of Combined Cycle Gas Turbine. International Journal of Energy Engineering, 2 (2012)1, pp. 9-14.63

[10] Khaliq A., Kaushik S., Thermodynamic Performance Evaluation of Combustion Gas Turbine Cogeneration System with Reheat. Applied Thermal Engineering, 24(2004), pp. 1785–1795.

[11] Mohagheghi M., Shayegan J., Thermodynamic Optimization of Design Variables and Heat Exchangers Layout in HRSGs for CCGT, using Genetic Algorithm. Applied Thermal Engineering, 29 (2009), pp. 290–299.

[12] Bracco S., Silvia S., Exergetic Optimization of Single Level Combined Gas Steam Power Plants Considering Different Objective Functions. Energy, 35(2010), pp. 5365-5373.
[13] Woudstra N., Woudstra T., Pirone A., Van der Stelt T., Thermodynamic Evaluation of Combined Cycle Plants. Energy Conversion and Management, 51(2010)5, pp. 1099–1110.
[14] Mansouri M. T., Ahmadi P., Kaviri A. G., Exergetic and Economic Evaluation of the Effect of HRSG configurations on the Performance of Combined Cycle Power Plants. Energy Conversion and Management, 58(2012), pp. 47–58.
[15] Xiang W., Chen Y., Performance Improvement of Combined Cycle Power Plant Based on the Optimization of the Bottom Cycle and Heat, Recuperation, Thermal science,16(2007), pp. 84-89.

Nomenclature

Symbols/Subscript

ED	Exergy destruction
Qs1	Heat addition to combustion chamber
Qs2	Heat addition to HRSG
Qs3	Heat transfer to HRB
HRB	Heat recovery boiler
GT	Gas turbine
ST	Steam turbine
OT	Organic turbine
W	work
C	compressor
P	pump
m	mass flow rate
CC	combustion chamber
HRSG	Heat recovery steam generator
ORC	Organic Rankine cycle
a	Air
COND	Condenser
ἠ	Efficiency