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Thermodynamic (energy-exergy) analysis of combined cycle power plant for improving thermal energetic and exergetic efficiencies by integration of organic Rankine cycle (ORC)

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Abstract

The exergy analysis (second law analysis) is used for providing information about the losses qualitatively as well as quantitatively along with their locations. Exergetic (thermodynamic) optimization improves the performance of a system by reducing the exergetic inefficiencies (exergy destruction and exergy losses) and increasing exergetic efficiency. The primary objective of this work is to utilize the waste heat from the stack which is coming from HRSG by integration of ORC plant with combined cycle. Then thermodynamic analysis is done .After comparison it is found that the system overall thermodynamic efficiencies (thermal and exergetic) are improved by integration of ORC system to existing combined cycle. Thermal efficiencies are improved by 3.32% and 4.09% first law and second law (exergetic efficiency) respectively. There is also separately calculation is done for each component. A program code is established to perform the calculations required for the exergy plant analysis considering 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 presented in this paper.

Key words: combined cycle, ORC, heat recovery steam generator, exergy, efficiency improvement, gas turbine

1. Introduction

Energy systems contain a colossal 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).

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. Advancement of energy change frameworks turns out to be more vital because of impediments of non-renewable energy sources and the ecological effect amid their utilization. The utilization of energy is discovered wherever in an assortment of uses from warming and cooling to atomic power plants. For a considerable length of time, the reaction to the constantly developing requirement for electric era limit was to manufacture another steam power plant, one not altogether different from the past one. The energy transformation engineer is confronted with an assortment of issues today: rising advances, changing the social and technological climate in which a differing qualities of methodologies is probably going to be acknowledged.

Some critical qualities of new power activities are low capital and working costs, capacity to work with an assortment of energizes and with high resistance to fuel fluctuation, short development time, low emanation of toxins, attractive or possibly dormant and effortlessly expendable waste items, and high efficiency, maintainability, finance ability, and reliability. Ordinarily, first law analysis gives just energy usage situation regarding preservation of energy. In any case, it can't give the

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data with respect to the losses both subjectively and quantitatively, and can't discover the area of these losses. These constraints compel 3 Another main problem faced by the energy conversion engineer is the finiteness of natural resources critically important for human beings (such as natural gas and oil) in 2 the world and ever-increasing energy demands by developing countries. Maybe future power plants ought to use coal and nuclear energy to spare the flammable gas and oil for mechanical sustain stocks and other more basic Established thermodynamics gives the idea of energy, energy transfer by heat and work, energy balance, entropy and entropy adjust and estimations of thermodynamic properties at balance. The second law of thermodynamics upgrades an energy balance by ascertaining the genuine thermodynamic estimation of an energy balance and genuine thermodynamic inefficiencies and losses from the procedure and framework. Exergy is the greatest valuable work achievable from an energy carrier under the given natural conditions. The exergy of an energy carrier is a thermodynamic property that relies on upon both the condition of the carrier being considered and the condition of nature. It communicates the greatest ability of the energy balance to bring about changes. Along these lines, energy is firmly identified with the financial estimation of the balance since clients pay the capability of energy to bring about changes. At the point when expenses are doled out to energy balance, exergy ought to fill in as a premise in the costing procedure. us to perform exergy examination in view of second law of thermodynamics. Exergy is not a conserved property but rather some of it is demolished in the genuine process. Exergy investigation gives a uniform base for correlation of different thermodynamic procedures. This analysis demonstrates the data with respect to losses that incorporate their area subjectively and quantitatively. This data can be utilized for further change in the outline and operation of the framework. By finding the exergy destruction, the system performance can be enhanced by enhancing the exergetic proficiency of the component and the system.

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 integration of ORC and 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 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 without integration of ORC. Furthermore, the optimization can be analysed 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 efficiency improvement method.

3. Analysis and Optimization of Topping Cycle

3.1 Thermodynamic Analysis and Optimization

The gas turbine operating parameters which influence the combined cycle gas turbine performance are; ambient conditions, compressor pressure ratio, and turbine inlet temperature.

3.2 The Effect of Ambient Conditions

One of the factors that affect gas turbine performance is the ambient conditions, mainly ambient temperature, atmospheric pressure, and the relative humidity of air. These parameters affect the generated electric power and the heat-rate during operation. The location of power plant plays a major role on its performance. The atmospheric air, which enters the compressor, becomes hotter after compression and it is directed to a combustion chamber. Several authors reported the effect of ambient temperature: 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. Ibrahim and Rahman [9], and Khaliq and Kaushik et al [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.

3.3 Analysis and Optimization of Bottoming Cycle

The efficiency of steam power plants can be improved by increasing the live steam and reheat-steam parameters, and by introducing high-efficiency, low-loss turbine blade geometries. The first goal, to increase the steam parameters, is primarily achieved by choosing appropriate materials for the components operating under live-steam and reheat-steam conditions while retaining the proven designs. Collaborative European programs have led to the development and qualification of steels with much improved creep properties at temperatures of up to 600 °C, appropriate for the manufacture of key components. At the same time, optimization of the blade profiles and geometries allowed further major improvements in operating efficiency. The achievable improvements in efficiency is about 0.5% per 10 °C live steam and reheat (RH) temperature increase, and 0.2 % per 10 bar pressure increase. Second important part of the bottoming cycle is the heat recovery steam turbine (HRSG), its design and optimization affects to a large extent influence the efficiency and the cost of the whole plant. Mohagheghi and Shayegan et al [13] performed the thermodynamic optimization of design variables and properties of air entering combustion chamber depend upon the compressor pressure ratio. 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 modelling 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 analysed. Bracco and Silvia [14] 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 [15**]** 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 [16] 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 Xiang and Chen [17] 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. Moreover, they highlighted the influence of the HRSG inlet gas temperature on the bottoming cycle efficiency. They studied the influence of HRSG inlet gas temperature on the steam bottoming cycle efficiency. Their result shows that increasing the HRSG inlet temperature has less improvement to steam cycle efficiency when it is over 590ºC. Kelly et al [18] demonstrated that the most efficient way for converting solar thermal energy into electricity is to withdraw feed water from the heat recovery steam generator (HRSG) downstream of the last economizer, to produce high pressure saturated steam and to return the steam to the HRSG for superheating and reheating. The integrated solar plant concept offers an effective means for the continued development of parabolic trough technology. In a careful plant design, solar thermal to electric conversion efficiencies will exceed, often by a significant amount, those of a solar-only parabolic trough project. An integrated plant bears only the incremental capital cost of a larger Rankine cycle which provides further reductions in the levelized cost of solar energy.He Ya Ling et al [19] proposed a model for a typical parabolic trough solar thermal power generation system with Organic Rankine Cycle (PT-SEGS–ORC) was built within the transient energy simulation package TRNSYS. They found that the heat loss of the solar collector (qloss) increases sharply with the increase in Pinter at beginning and then reaches to an approximately constant value. The variation of heat collecting efficiency with v is quite similar to the variation of gloss with Pinter. However θ exhibit opposite effect on η_{hc}. In addition, it is found that the optimal volume of the thermal storage system is sensitively dependent on the solar radiation intensity. The optimal volumes are 100, 150, 50, and 0 m3forspring equinox, summer solstice, autumnal equinox an proposed d winter solstice, respectively Gang et al [20] the innovative configuration of low temperature solar thermal electricity generation with regenerative Organic Rankine Cycle (ORC) mainly consisting of small concentration ratio compound parabolic concentrators (CPC) and the regenerative ORC. The effects of regenerative cycle on the collector, ORC, and overall electricity efficiency are then analyzed. The results indicate that the regenerative cycle has positive effects on the ORC efficiency but negative ones on the collector efficiency due to increment of the average working temperature of the first-stage collectors. And found that there generative cycle optimization of the solar thermal electric generation differs from that of a solo ORC. The system electricity efficiency with regenerative ORC is about 8.6% for irradiance 750 W/m^2 and is relatively higher than that without the regenerative cycle by4.9%.Manolakos D et al [21] proposed co-generation system producing electricity and fresh water by a solar field driven supercritical organic Rankine cycle (SORC) coupled with desalination. The proposed system can use parabolic trough solar collectors (among other options) to produce 700 kW thermal energy with temperatures up to 400°C at peak conditions. Thermal energy is delivered to the SORC which uses hexamethyldisiloxane (MM) as the working organic fluid and could achieve cycle efficiency close to 21%. The SORC condensation process is undertaken by the feed seawater to reduce thermal pollution. Due to the elevated temperature of the preheated seawater, the RO unit specific energy consumption decreases. Although , lot of literature 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 HGRC. Almost flue gas around 150-180 ^{0}C is going to waste from stack.

After reading literature review it is concluded that no researcher use the energy at temperature 150-180^{0}C from the flue gases.

In this research 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. It is proposed to examine the effect of the various parameters on the performance of the combined cycle and comparison is done with or without integration of the ORC. These parameters are following

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

4. Thermodynamic Analysis

For thermodynamic analysis (exergetic and energetic) a model is proposed in this model there are following components

- Compressor
- Combustor
- Gas turbine
- HRSG
- Steam turbine
- Condenser
- Heat recovery boiler
- Organic pump
- Water pump
- Organic surface condenser

4.1 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 vapor 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.

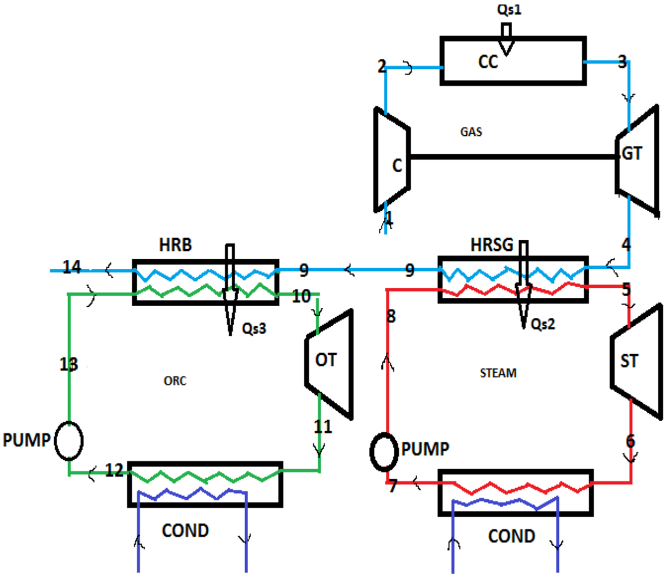

Figure 1: Thermodynamic model of combined cycle with Organic Rankine cycle (ORC)

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 vapor.

5. No pressure loss in HRSG and heat recovery boiler.

4.2 *Energy Analysis*

In this system I consider the whole system is control volume. Each component of the whole system is separately considered as control volume. The equations are given as
Mass balance

$$\sum m_{in} = \sum m_{out}$$

Energy balance

$$Q - W + \sum m_{in} - \sum m_{out} = 0$$

Overall thermal efficiency of plant without ORC

$$\acute{\eta}_{without\ ORC} = (W_{GT} + W_{ST} - W_C - W_P) / Q_{s1}$$

Overall thermal efficiency of plant with ORC

$$\acute{\eta}_{with\ ORC} = (W_{GT} + W_{ST} + W_{OT} - W_C - W_P - W_{OP}) / Q_{s1}$$

4.3 *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 for each component is also calculated from above question
Exergy transfer in combustion chamber from fuel is given as
$ET = Q_{S1}*[1-T_0/T_C]$
Overall exergetic efficiency of plant without ORC

$$\acute{\eta}_{exergetic\ without\ ORC} = (W_{GT} + W_{ST} - W_C - W_P) / ET$$

Overall exergetic efficiency of plant with ORC

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

5. Results and Discussion

This thermodynamic model developed by engineering question solver (EES commercial version).The calculation of efficiencies is done by this software and results have been calculated. Comparison is done in figures .From figure 2 to figure 3 the exergetic efficiency vs pressure ratio and air fuel given respectively and compare with and without ORC .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 out put hence exergetic efficiency increases. On other hand decrease in 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 4 and 5 shown the variation of thermal efficiency with respect to the pressure ratio and air fuel ratio respectively and compared efficiency with and without ORC. Same effects are calculated as well as exergetic efficiency. Here also same reason for increase and decrease of thermal efficiency with pressure ratio and air fuel ratio as exergetic efficiency. Input parameters taken for study are given below these parameters are taken from different running power plants. These are following

Ambient temperature	T_0=298K
Flue gases temperature from HRSG	T_9=423K
Constant pressure in HRSG	P_5=10bar
Temperature inlet to steam turbine	T_5=813K
Temperature inlet to organic turbine	T_{10}=403K
Pressure inlet to organic turbine	P_{10}=25bar
Pressure outlet to organic turbine	P_{11}=2bar
Pressure outlet to steam turbine	P_6=0.07bar
Outlet temperature of gases from HRB	T_{14}=300K
Organic fluid for ORC	R410A

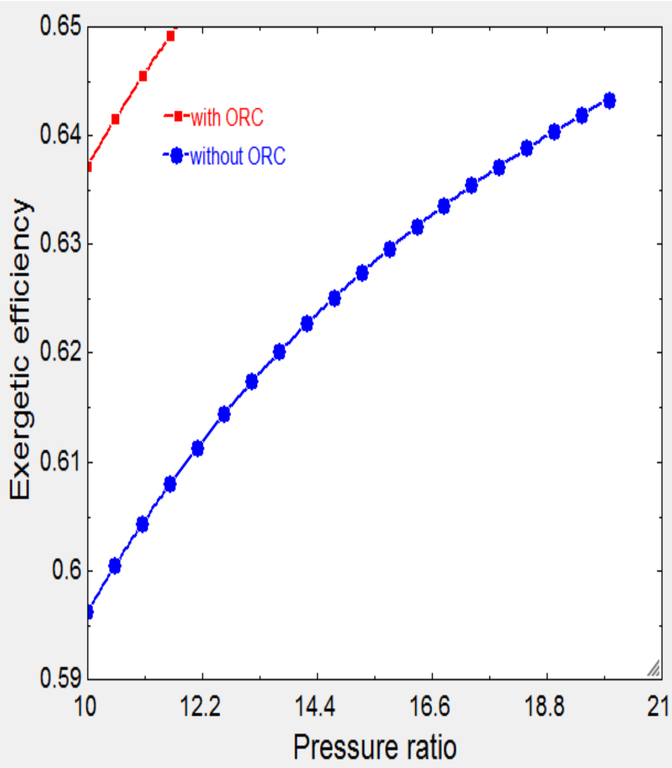

Figure 2: Exergetic efficiency vs pressure ratio

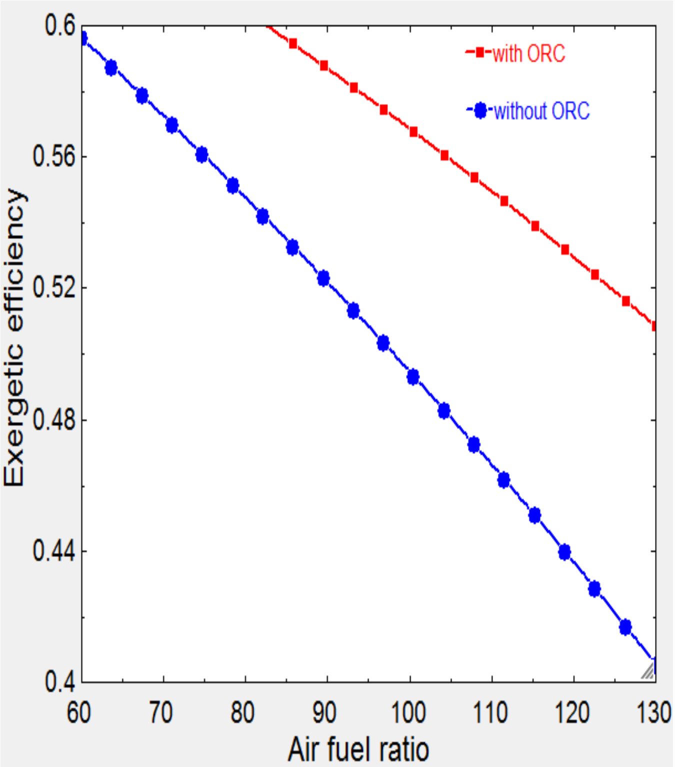

Figure 3: Exergetic efficiency vs air fuel ratio

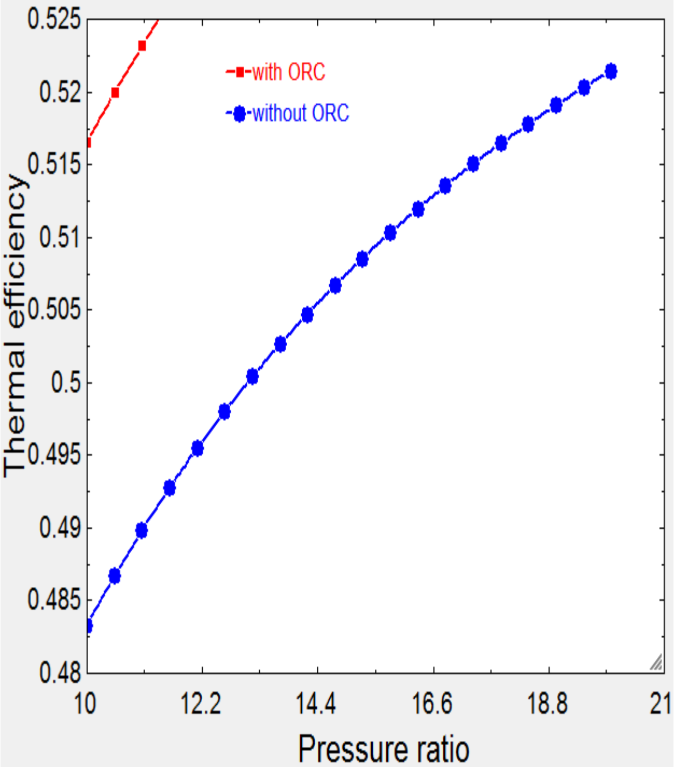

Figure 4: Thermal efficiency vs pressure ratio

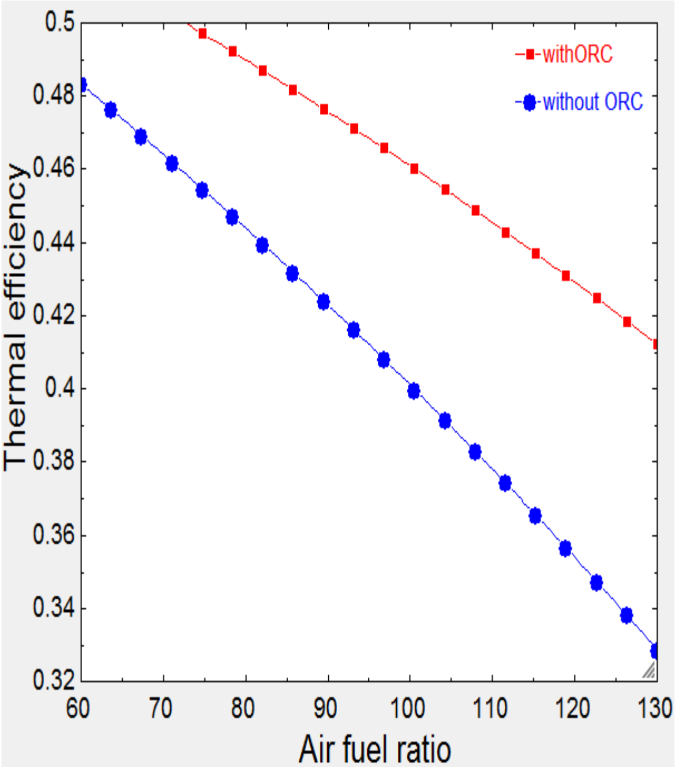

Figure 5: Thermal efficiency vs air fuel ratio

6. Conclusions

The numerical computations have been carried out for R 410a using thermodynamic (energy) analysis of combined cycle power plant by integrating of organic Rankine cycle the following conclusions are made

1. With ORC exergetic efficiency is more than without ORC.
2. With ORC thermal efficiency is more than without ORC.
3. So integration of ORC with the existing combined cycle is effective.
4. So heat from the exhaust gases is fully utilized by integration of ORC.

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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
ἡ	Efficiency
HRSG	Heat recovery steam generator
ORC	Organic Rankine cycle
a	Air
COND	Condenser