The International Journal of Engineering and Information Technology

journal homepage:www.ijeit.misuratau.edu.ly

Performance Analysis of a Solar Cogeneration Power Combined Cycle at Variable Operational and Design Conditions

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Abstract— **This paper is to investigate the performance of a solar cogeneration power combined cycle(SCPCC), in which a computer program, called " SCPCC Design" has been developed using MATLAB for the analysis. In addition the System Advisor Model (SAM) software has been used in the analysis. Here, many operational and design parameters are taken in consideration to determine the overall efficiency of the proposed cycle, such as compressor pressure ratio, combustion temperature in the gas turbine unit, inlet steam pressure, exhaust gases temperature and process heat mass fraction. The solar thermal energy obtained from the solar field is obtained according to the specifications of Libyan Capital, Tripoli City, and through all the year. The results obtained from this study have shown a clear influence for these parameters on the overall efficiency, where it increases with combustion temperature, steam pressure and mass fraction, while it decreases with compressor pressure ratio .**

Index Terms: **performance, solar, cogeneration, power plant, Tripoli.**

I. INTRODUCTION

The production of electrical energy in most countries of the world depends mainly on combustion processes by conversion thermal energy of fossil fuels to a mechanical energy through a certain power cycle which could be steam, gas, diesel or any combination of them. So for more than a century of using the fossil fuels this resource has been running out. However, globally talking, the present day energy scenario does not present an encouraging image. Fossil fuel depletion is very evident with the possibility of total exhaustion in a generation's time.

A huge energy crisis is foreseeable until, or unless, radical steps are taken to change the present course of energy attainment [1]. Primary energy consumption will continue to increase and reach 17,721 Mtoe in 2030 from about 9000 Mtoe in 1990. There are two reasons for this increase; namely rapid economic growth in developing countries, especially in Asia, and an explosion in the world's population [2]. Fossil fuel such as oil, natural gas and coal are finite energy sources. The International Energy Agency (IEA) [3] has estimated, that the peak period of conventional oil production would be in the 2030's, even in optimistic scenarios (a high resource scenario).

As a result the long term world energy problem, global warming, is another urgent issue because CO_2 emissions are caused by the combustion of fossil fuels[4]. According to the United Nations (UN) [5] , climate change is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to the natural climate variability observed over a comparable time period.

Libya is one of the oil production countries, and its economic depends mainly on this energy resource since mid-fifties of last century. The electric energy production in Libya is provided by gas-turbine, steam-turbine and combined cycle power plants, which use heavy oil, light oil and natural gas . Gas turbine and combined cycle power plants have a share of 30% and 20% respectively in total installed power capacity, the share of steam power plants is 50% in total in 2015. Furthermore, some small diesel power plants are also used to contribute to the energy supply, especially in remote areas [3,4].

This bad image of energy scenarios through the world due to the extensive consumption of fossil fuels and environmental impacts have been considered a potential motivation for global concern to concentrate on other alternative energy resources such as renewable energies, which are almost available abundantly in most of the world countries, and distinguishably in Libya . One of these resources is the solar energy which happens to be an active source for running the power plants among other renewable energy sources. Integrated Solar Combined Cycle (ISCC) power plants have gained popularity among the thermal power plants.

The ISCC system is a combination of a solar field and gas turbine-combined cycle. The waste heat from the gas

Received 23 Sep , 2021; revised 24 Oct, 2021; accepted 24 Oct, 2021.

Available online 18 Nov , 2021.

turbine is used to generate some steam to be expanded in a steam turbine. In addition, the solar field supplies extra heat to the thermal cycle. The additional heat from the solar field results in electricity generation increase during sunlight time. This combination results in improving the overall thermal efficiency . The benefits of employing this technology are to overcome some problems related to startup and shut down in solar power plants, reduce the capital cost and improve the solar-to-electricity efficiency [6].

Libya is very lucky in the availability of this inexhaustible energy source, where about 88% of its land area is desert, most of this area located in the heart of the sunbelt. The country is wealthy in solar radiation income with the daily average radiation on a horizontal plane being 7.5 kWh/m^2/day in the southern region in AlKufra and 6 kWh/m^2/day in the coastal region . The number of sunshine hours amounts to more than 3500 hours per year [7].

In some cases the combined cycles are designed to be cogeneration plants, which are used to produce power and heat from the exhaust gases for preheating air in furnaces, for absorption cooling systems, or for heating various types of fluids in different process applications.

Cogeneration systems are also used in petrochemical plants where the prime mover drives are used to drive compressors to compress process gasses and then the heat used to either produce steam for process use or for direct use in processes [8].

Cogeneration provides several environmental benefits by making use of waste heat and waste products and reduces air pollution by minimizing amounts of emissions, particularly CO_2 and NO_x . Also it reduces burden on existing limited fossil fuel supplies and positive stabilization of future fuel supply. Water pollution is also lessened by cogeneration systems [9].

Upon this importance of the cogeneration plants with ISCC this study is carried out to investigate the potential of improving the electricity generation system locally and the potential of the available clean energy resource powered by solar energy and to present and enhance efficiency of thermal cycles for power plants in Libya via an energy recovery of the exhaust gas out to the environment in order to increase the quantity and quality of steam entering the steam turbine. Thus the proposed study should be satisfied the following requirements:

- An optimum design and optimum arrangement of the main components of the plant working on the proposed cycle.
- To carry out a thermal analysis on the integration of conventional power plants with solar energy technology.

II. THE DESCRIPTION OF THE PROPOSED SOLAR/COGENERATION PLANT

The design proposed in this study is the solar cogeneration combined cycle. This system is composed of two main components, the solar field and the power block. The power cycle used for this design is a conventional combined cycle of gas turbine unit operating on natural gas and steam turbine unit, with a heat recovery steam generator (HRSG) in between. The thermal energy provided from HRSG and solar field are used for power production and heat process in the cogeneration unit, as shown in Figure 1. This configuration is attractive because it draws the environmental benefits from using solar energy with the operational advantages of the conventional combined cycle.

When the sun is not shining, the combined cycle power plant can be used as a backup for solar power. By integrating solar energy, the reduction of natural gas consumption is possible (fuel saver mode).

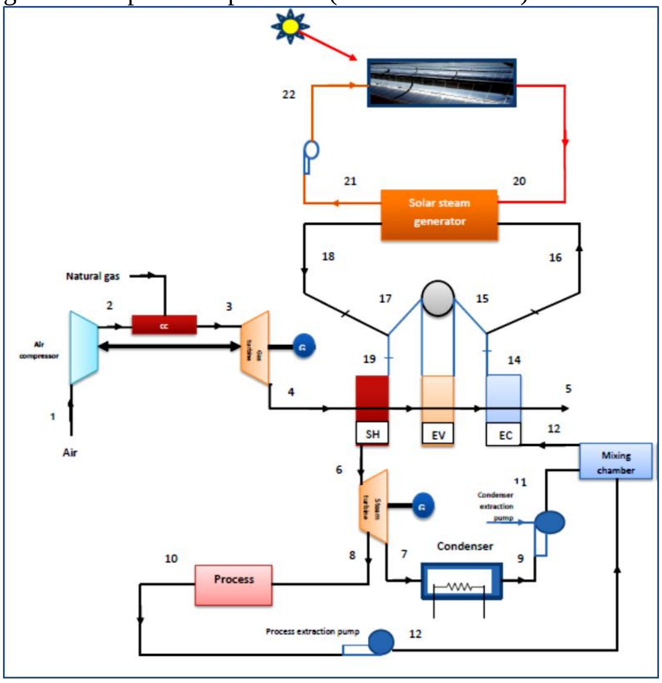

Figure 1. Schematic diagram of the solar/cogeneration plant

The solar field is parabolic trough system with heat transfer fluid (HTF) called Therminol VP1, which enters the loop with an inlet temperature of 293°C where it is circulated through the receiver and heated to an outlet temperature of 391°C. Afterwards, the HTF runs through a steam generator to generate high pressure steam. The generated steam passes then through the heat recovery steam generator (HRSG) . The steam gains input heat energy from the high temperature exhaust gases coming out of the gas turbine unit. The generated superheated steam produced thus can be used to drive the steam turbine and the process heat.

The steam turbine delivers the heat used in industrial processes and the energy to the generator drive shaft. The generator converts this energy into electricity and the discharged steam from the steam turbine is condensed into water that will be pumped back to a steam generator.

III. MATHEMATICAL MODELING OF THE SOLAR/COGENERATION PLANT

The mathematical modeling of this plant is done by formulating the performance parameters of each component based on first and second laws of thermodynamics with considering the working fluid is calorically perfect through the gas unit, thus specific heats at constant pressure are C_{pa}=1.005 kJ/kg K and C_{pg}=1.148 kJ/kg K, and the heating process is direct in the solar field.

Also the gas turbine unit is of simple type with constant isentropic efficiencies of the gas turbine and the compressor in all cases.

A. Analysis of the Gas Turbine unit

In the gas turbine cycle, low-pressure air is drawn into a compressor (state1) where it is compressed to a higher pressure (state2). Fuel is added to the compressed air and the mixture is burnt in a combustion chamber. The resulting hot products enter the turbine (state 3) and expand to state 4 (see Figure. 1) . This expansion of the hot working fluid produces a great power output from the turbine. Most of the work produced in the turbine is used to run the compressor and the rest is used to run auxiliary equipment and produce power.

The work of the compressor W ̇_C can be given from the following relation [10] :

$$\dot{W}_C = \frac{C_{pa}.T_1\left[r_p^{\left(\frac{\gamma-1}{\gamma}\right)}-1\right]}{\eta_m.\eta_c} \quad (1)$$

Where:

C_{pa} is the specific heat of air (J/kg k).

η_m is the mechanical efficiency of the compressor and turbine.

B. Combustion Chamber

The energy balance equation of the combustion chamber is [47]:

$$\dot{m}_a C_{pa}.T_2 + \dot{m}_f LHV + \dot{m}_f.C_{pf}.T_f = (\dot{m}_a + \dot{m}_f)C_{pg}.T_3 \quad (2)$$

Then the fuel-air ratio f can be expressed as follows:

$$f = \frac{\dot{m}_f}{\dot{m}_a} = \frac{C_{pg}.T_3 - C_{pa}.T_1(1+R_{pg})}{LHV + C_{pf}.T_f - C_{pg}.T_3} \quad (3)$$

Where:

$$R_{pg} = 1 - \frac{1}{r_p^{\frac{\gamma_g-1}{\gamma_g}}} \quad (4)$$

C. Gas Turbine

The shaft work of the turbine $\dot{W}_t$ is given by:

$$\dot{W}_t = \frac{C_{pg}.T_3.\eta_t.R_{pg}}{\eta_m} \quad (5)$$

The net work of the gas turbine unit is calculated from the difference of the turbine work and the compressor work as:

$$\dot{W}_{Gnet} = \dot{W}_t - \dot{W}_c \quad (6)$$

The specific fuel consumption SFC is determined from:

$$SFC = \frac{3600.\dot{m}_f}{\dot{W}_{Gnet}} \quad (7)$$

The heat supplied is expressed as:

$$\dot{Q}_{add} = f.LHV \quad (8)$$

The gas turbine efficiency is given by:

$$\eta_{GT} = \frac{\dot{W}_{Gnet}}{\dot{Q}_{add}} \quad (9)$$

D. Heat Recovery Steam Generator

The HRSG consists of three main parts which are the economizer, the evaporator and the superheater. This single pressure model is a common type for the combined cycle power plant. The energy balance equations are shown next [11].

The gas temperature and water properties are calculated using pinch analysis. The designed pinch point T_{pp} and approach point T_{ap} is shown in Figure 2.

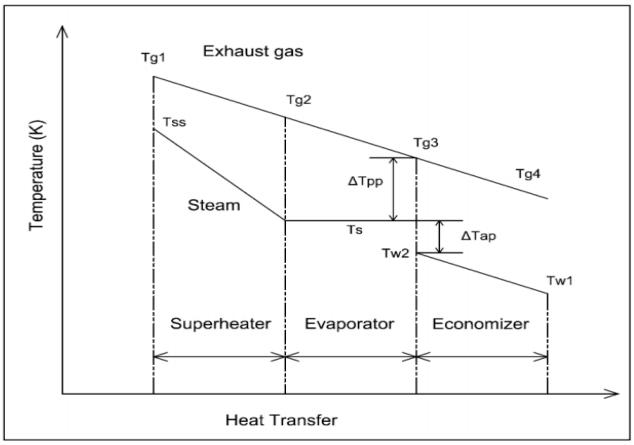

Figure 2. Temperature profile in Heat Recovery Steam Generator

The temperature of gas leaving the evaporator T_{g3} is:

$$T_{g3} = T_S + \Delta T_{PP} \quad (10)$$

Where:

T_s is the saturation steam temperature.

The inlet water temperature T_{w2} to the evaporator is given by:

$$T_{w2} = T_s - \Delta T_{ap} \quad (11)$$

The available heat from the gas turbine exhaust can be expressed as:

$$\dot{Q}_{av} = \dot{m}_g.C_{pg}.(T_{g1} - T_{g3}).h_{lf} \quad (12)$$

Where

$\dot{m}_g$ gas flow rate (Kg/s)

h_{lf} the heat loss factor which is in the range of (0.98-0.99).

The steam flow rate $\dot{m}_s$ is found from the relation:

$$\dot{m}_s = \frac{\dot{Q}_{av}}{(h_{sh}-h_s)+BD.(h_s-h_{w2f})} \quad (13)$$

Where

BD is the blow down factor and defined as the part of water that is purposely drained during the boiler operation to limit the level of impurities in boiler water to an acceptable level..

The gas temperature entering the evaporator T_{g2} is:

$$T_{g2} = T_{g1} - \frac{\dot{m}_s.(h_{sh} - h_s)}{h_{lf}.\dot{m}_g.C_{pg}} \quad (14)$$

The duty of the superheater can be obtained from the following equation:

$$\dot{Q}_{sh} = \dot{m}_s.(h_{sh} - h_s) = \dot{m}_g.C_{pg}.(T_{g1} - T_{g3}).h_{lf} \quad (15)$$

The water flow rate $\dot{m}_w$ is given by:

$$\dot{m}_w = \dot{m}_s.BD \quad (16)$$

Finally, the stacks exhaust temperature T_{g4} leaving the HRSG is:

$$T_{g4} = T_{g1} - \frac{\dot{m}_s.BD.(h_{w2f} - h_{w1f})}{\dot{m}_g.C_{pg}} \quad (17)$$

E. Solar Steam Generator

The solar steam generator is used to raise the temperature of the feeding water in the steam cycle by exchanging heat with the thermal energy of the heat transfer fluid from the solar concentrator . The energy balance equation of the solar steam generator is:

$$\dot{m}_{HTF}.C_{pHTF}(T_{20} - T_{21}) = \dot{m}_w.(h_{18} - h_{16}) \quad (18)$$

F. Steam Turbine

The superheated steam with high pressure obtained from the HRSG is then expanded through the steam turbine where the steam turbine work $\dot{W}_s$ can be given as [10]:

$$\dot{W}_s = \dot{m}_s.h_6 - \dot{m}_s.(1-y)(h_7) - \dot{m}_s.y(h_8) \quad (19)$$

G. Condenser

The heat rejected from the condenser Q_{cond} is given from:

$$\dot{Q}_{cond} = \dot{m}_w.(1-y)(h_7 - h_9) \quad (20)$$

H. Heat Processes

The amount of heat needed for processing is given by :

$$\dot{Q}_{process} = \dot{m}_s.(y)(h_8 - h_{10}) \quad (21)$$

I. Pump

The pump work $\dot{W}_P$ from extracting the condensate water to the economizer is:

$$\dot{W}_P = \dot{m}_w.y.(h_{12} - h_{10}) + \dot{m}_w.(1-y)(h_{11} - h_9) \quad (22)$$

Therefore, the net work of the steam turbine W_{snet} is calculated from:

$$\dot{W}_{snet} = \dot{W}_S - \dot{W}_P \quad (23)$$

The efficiency of the steam turbine unit is:

$$\eta_{st} = \frac{\dot{W}_{snet}}{\dot{Q}_{av}} \quad (24)$$

The efficiency of the combined cycle can be given by [8]:

$$\eta_{cc} = \eta_{GT} + \eta_{st} - (\eta_{st}.\eta_{GT}) \quad (25)$$

J. SCPCC Efficiency

Finally, the overall efficiency of the Solar Cogeneration power Combined Cycle plant is:

$$\eta_{SCPCC} = \frac{\dot{W}_{snet} + \dot{W}_{Gnet} + \dot{Q}_{Process}}{\dot{Q}_{add} + \dot{Q}_S} \quad (26)$$

Where

$\dot{Q}_S$ is the thermal energy received from the solar field.

IV. RESULTS AND DISCUSSION

To carry out the analysis two softwares have been used to obtain the results, first one is “The SCPCC Design”, which is a computer program written using MATLAB, for conceptually designing solar cogeneration power combined plants. The second software is the System Advisor Model (SAM) version 2018.

The proposed location for the system is Tripoli . This location was selected because it has a high level of direct solar irradiation, and easy connection to the existing power and gas grid infrastructure. Its location also contributes to the Tripoli's economic development goals by spurring economic activity in the Western Region.

The distribution of the beam normal irradiance through all the year for Tripoli (in W/m^2) is given by Figure. 3, while the field thermal power absorbed is given by Figure. 4.

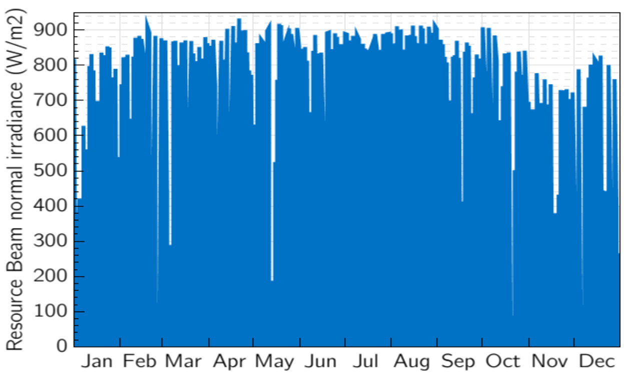

Figure 3. The distribution of beam normal irradiance for Tripoli through all the year

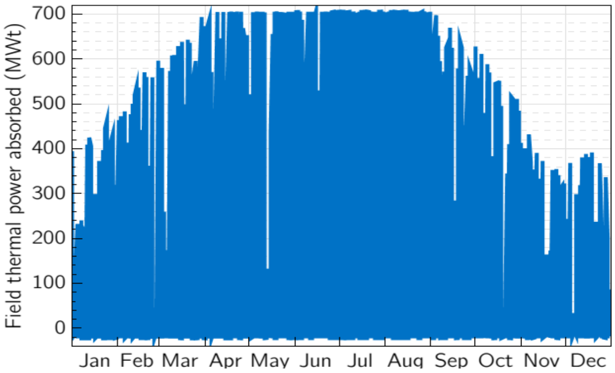

Figure 4. The distribution of the field thermal power absorbed through the year

A. Effect of gases mass flow rate on the overall efficiency of the plant

Figure 5 shows arise in the efficiency of the solar cogeneration power combined cycle when increasing the gas flow rate. The overall efficiency increased from 38% at a flow rate of 100 kg/s to around 77% at the flow rate of 200 kg/s, at The design input value for the gas turbine inlet temperature (T_3) was 1100°C. These results were obtained at an ambient temperature of 35°C and a compressor pressure ratio of 6:1 for the compressor.

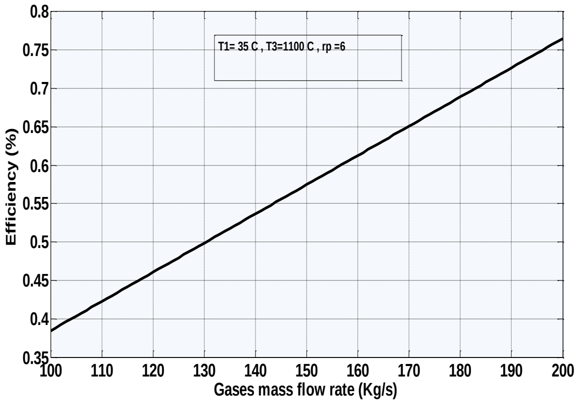

Figure 5. Relationship between the efficiency and the gases mass flow rate

B. Effect of the compressor pressure ratio on the efficiency

At a certain combustion temperature the efficiencies are influenced by compressor pressure ratio as shown in Figure. 6. Here we notice that there is drop in the overall efficiency compared with that of gas turbine or combined cycle. The efficiency values for the SCPCC system were decreasing from about 70% to 43% and the efficiency for combined cycle increased from 49% to 54% while the gas turbine efficiency varied slightly.

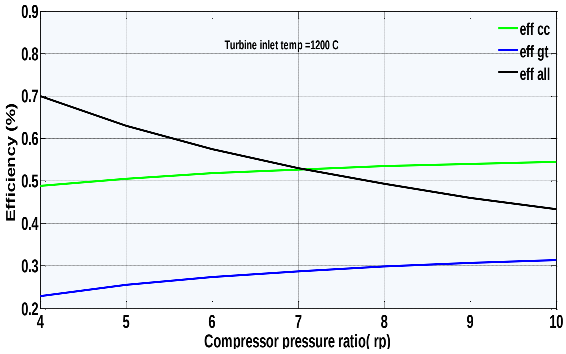

Figure 6. Relationship between efficiencies and compressor pressure ratio

C. Effect of Temperature exhaust gases outlet from HRSG on the overall efficiency of the plant

In Figure. 7 the efficiency increases with decreasing temperature exhaust gases outlet from HRSG from 62% at 395 k to 35.5% at about 480K

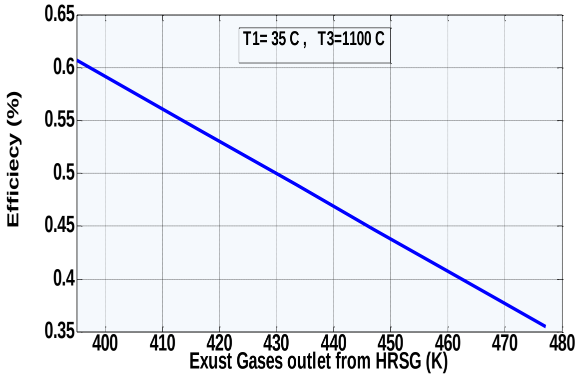

Figure 7. Relationship between the overall efficiency and the exhaust gases temperature

D. Effect of Turbine inlet pressure for steam turbine on the overall efficiency of the plant

It's clear from Figure. 8 , that the efficiency increases when the steam turbine inlet pressure increases, in which at r_p= 4 :1 the efficiency increases from 60 % at inlet pressure = 60 bar to 63% at inlet pressure = 120 bar at a certain value of compressor pressure ratio (***r_p***), but it is going down with increasing ***r_p***. This means that at higher inlet pressures we can obtain more output power from steam unit, while at higher CPR the output power well decrease because the compressor needs more energy in favor of total output power.

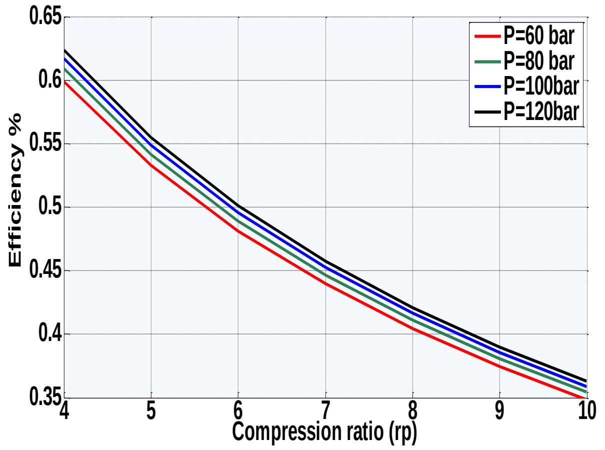

Figure 8. Relationship between overall efficiency and steam turbine inlet pressure

E. Effect of the Process mass fraction on the overall efficiency of the plant

Another important parameter for efficient operation is the process mass fraction (y) . Figure 9 shows that at a certain compressor pressure ratio , the overall efficiency increases with increasing the process mass fraction (y). This because more processing heat can be obtained by increasing the mass fraction, which is one of the outputs of the cycle that reflected positively on the overall efficiency.

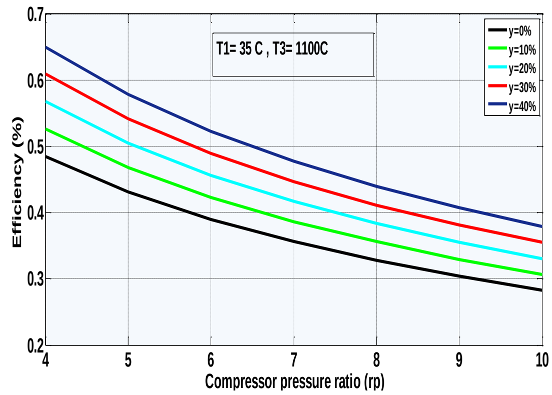

Figure 9. Relationship between the overall efficiency and the process mass fraction

V. CONCLISIONS

This study has been to investigate the solar cogeneration power combined cycle plant (SCPCC) , where a mathematical modeling has been developed to analyze the SCPCC power plant operating under Libyan climatic conditions. From the results obtained at a design and operational parameters it is concluded the following :

1. The efficiency of the solar cogeneration power combined cycle increases when increasing the gas flow rate significantly.
2. The overall efficiency of the cycle increases with increasing the gas turbine inlet temperature, at a certain compressor pressure ratio , say 4:1, the overall efficiency increases to 60%,70% ,80%, 90% at gas turbine inlet temperature equal 1100°C ,1200°C,1300°C, 1400°C respectively.
3. The overall efficiency increases with increasing the temperature of the gas outlet from the gas turbine from 35% at 835 K to 62% at 1020 K .
4. Also at a certain compressor pressure ratio(r_p) , say 4 :1, the overall efficiency increases from 60 % at inlet pressure for steam turbine = 60 bar to 63% at inlet pressure for steam turbine = 120 bar .
5. The overall efficiency increases from 53% ,56.4%, 61%, 65% at the process mass fraction (y) = 10%, 20%, 30%, 40% respectively at the same compressor pressure ratio, say 4:1.

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