Thermodynamic analysis of Ethanol and Diesel Fueled SOFC based Gas Turbine Combined Cycle Power Plant

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Abstract

When the fuel cells are integrated with the gas turbines, the total thermal efficiency of the combined cycle can be achieved greater than 70%. This is appreciably better exergetic performance when compared to traditional gas turbine cycle. In thepresent study, thermodynamic analysis of SOFC-GT hybrid system has been carried out, to evaluate energy efficiency, exergy efficiency and exergy destruction of each component is calculated. The effect of pressure ratio (r_p), turbine inlet temperature (TIT), air fuel ratio and ambient temperature of air, on the performance of the system has been analyzed by adopting the different fuels. The outcome of the system modeling reveals that SOFC and combustion chamber are the main sources of exergy destruction. SOFC-GTsystems are fuel flexible and scalable. When ethanolis used as fuel, at the optimum pressure ratio 9, the total thermal efficiency is found to be 61.36% and the exergy efficiency is obtainedas55.14%.Similarly when Diesel is used as fuel, at the optimum pressure ratio 9, the total thermal and the exergy efficiencies are obtained as70.72 and 66.76%.respectively.

Keywords: -SOFC, gas turbine, exergy, exergy destruction, combined cycle

1. INTRODUCTION

Nernst was the first to describe Zirconia (Z_rO_2) as an oxygen ion conductor in the year 1899 [1]. Nowadays, a century later, Zirconia is still the most common electrolyte material in SOFCs with addition of small percentage of yittria (Y_2O_3). However, manufacturing methods and design have been improved to give higher reliability, efficiency and power density. The SOFC system usually utilizes a solid ceramic as the electrolyte and operates at high temperature (973-1273K) and this high temperature is beneficial for co-generation of both electricity and high-grade heat, which can be further utilized in a bottoming cycle, thus, increasing total system efficiency of more than 65%. This high operating temperature allows internal reforming, promotes rapid electro catalysis with non-precious metals and produces high quality byproduct heat for co-generation. With an operating temperature of around 1000^0c, the emissions of pollutants such as NO_x are likely to be very small. Also, Sulphur Compounds must be removed from the fuel cell and hence SO_x – emissions are negligible [2]. SOFCs are best suited for stationery power generation systems due to significant time required to reach operating temperatures. However, high operating temperature imposes restrictions on materials which can otherwise be effectively used for designing a complete device. Lowering of FC performance occurs over a period of time and is related to the deterioration of material properties and interfacial reactions between various fuel cell components [3].

In an anode supported planar design SOFC, the anode consists of nickel and yttria stabilized Zirconia (YSZ), the electrolyte of YSZ and the cathode of lanthanum strontium magnatitute (LSM) and YSZ [4].

A hybrid system consisting of gas turbine and SOFC achieves electrical efficiencies (>60%) that are comparable to other large combined power plants. High temp fuel cells like SOFC, MCFC have much potential to achieve high efficiency for electricity production and they are already in use in USA[5].

If a SOFC is pressurized, the performance is improved with the increase in voltage. However the improved performance allows to integrate the SOFC with a gas turbine, which needs a hot pressurized gas flow to operate. Since the SOFC stack operates at 1000°C it produces a high temperature exhaust gas. If it is operated at an elevated pressure, the exhaust becomes a hot pressurized gas flow that can be used to drive a turbine. If SOFC is pressurized and integrated with a gas turbine, the pressurized air needed by the SOFC can be provided by the gas turbine's compressor, the SOFC can act as the combustor, and the exhaust from the SOFC through combustion chamber can drive the compressor and a separate generator.

Electrical Power is thus generated by the SOFC (DC) and the generator (AC) using the same fuel/air flow. The thermal efficiency of conventional GT plants is about 40%, while GT's integrated with SOFCs/MCFCs will have an efficiency of 56%-76% [6] with different types of configurations. The literature survey reveals that a few research articles [6-9] have been presented the exergy analysis of each component of the hybrid system.

Siemens-Westinghouse power company developed the tubular SOFCs for different applications of stationary power generation. By integrating the SOFC stacks with gas turbine and pressuring the system(PSOFC/GT),the efficiencies as high as 70-75% could be obtained [10].Chan e*t al*.[11,12] modeled a simple SOFC-GT power plant and presented that an internal reforming hybrid SOFC/GT system could get an electrical efficiency of more than 60 %.Song e*t al*[13] studied the possible extension of a SOFC/GT hybrid system to multi MW power generation system based on a commercially available gas turbine and thermo economic analyses of SOFC/GT hybrid systems. SOFC systems were also analysed by Calise*et al.* [14-17].Also Zhang *et al* [18] showed integration strategies for SOFCs.

Douvartzides*et al* [19,20] presented an energy-exergy analyses to optimize the operational conditions of a SOFC/GT power plant, by considering only the hydrogen oxidation within the fuel cell and rejecting the effect of the cell losses instead of methane reforming and carbon monoxide conversion. The optmal condition was obtained for a SOFC fuel utilization factor of 79.85%,an ethanol conversion of 100%,water to ethanol ratio 3:1 and no energy integration was observed. Granovskii*et al*[21] compared the performance of two combined SOFC-GT systems. A thermodynamic analysis of a combined gas turbine power system with a solid oxide fuel cell was carried through exergy by Haseli*et al*.[22].The application of YttriaStabilised Zirconia anodes in SOFC systems allows the conversion of methaneinto hydrogen and corbon monoxide on their surfaces. This consists of two simultaneous processes[1,23]:methane conversion to synthesis gas (internal reforming) and electricity generation via oxidation of the synthesis gas. The cogeneration efficiencies of fuel cell systems also have been evaluated and compared with exergymethods[24,25].Zhu and Kee[26] studied the impact of the fuel utilization factor on SOFC efficiency using a detailed electrochemical model and generated efficiency maps which give the range of methane-steam mixtures for maximum efficiency.

The exergy analysis of combined cycle power generation unit gives the details of exergy efficiency, exergy loss and exergy destruction for individual components in the plant and also for the overall plant and their variation with operating parameters.[27].The pressure ratio(r_p) and the turbine inlet temperature are the key parameters in the analysis of combined cycle power plant[28].

The main objective of the present work is to investigate the performance of GT-SOFC plant with its exergetic losses for different fuels. It also develops the efficient operating conditions.

2. GAS TURBINE – FUEL CELL SYSTEM THERMODYNAMIC CONFIGURATION

Figure.1 shows the configuration of a gas turbine-SOFC combined cycle. The system is fed with the fuel to SOFC and combustion chamber. The air is pressurized in the compressor and preheated in the recuperator, is supplied into the cathode of the fuel cell. The outlet air from cathode is used to burn the residual hydrogen, carbon oxide and fuel in the anode outletgas. The products of chemical reaction are very lean, hence additional amount of fuel is injected into the combustion chamber in order to stabilize the combustion. The extra fuel is supplied not for increasing the turbine inlet temperature.

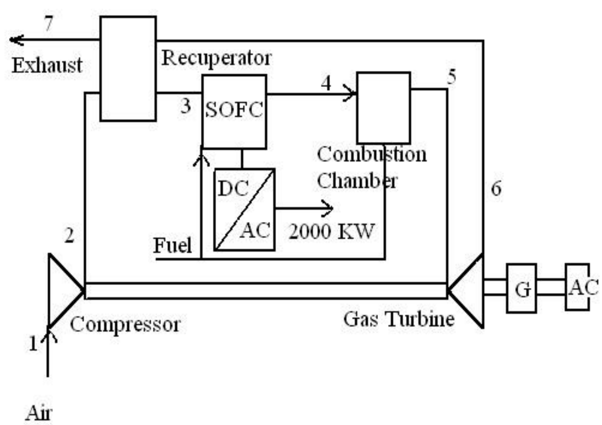

Figure:1 Layout of the Gas turbine – Fuel Cell Combined cycle Power generation system.

The flue gas from combustion chamber is expanded in the turbine and preheats the compressor outlet air in the recuperator.

For the analysis of the plant a computer program has been developed which consists of several control loops to calculate fluid thermodynamic properties and exergy values at various states. The effects of various parameters, such as compressor pressure ratio, turbine inlet temperature, air fuel ratio and ambient temperature are studied on the plant performance.

Table: 1 Standard cycle analysis conditions and input parameters for the simulation

SOFC	**Properties of fuels [29]**
Fuel utilization factor(U_f):85% Air utilization factor(U_a): 25% SOFC stack temp : 1273K(T_{stack}) Current density : 0.3A/cm^2 Cell voltage=0.7127V Cell area(A_c): 834 cm^2 DC power output from fuel cell stack=2000 kW	DC – AC Inverter Efficiency:$(\eta_{inverter})$: 0.89 LHV of ethanol : 26747.86 kJ/kg Specific chemical exergy of [29] Ethanol ; 29746.01 kJ/kg HHV of Diesel($C_{12}H_{26}$) : 44800 kJ/kg Specific chemical exergy of [3] Diesel :47230J/kg

2 System Modeling

Plant layout is shown in Fig.1. The thermodynamic performances of all the components of the system are analyzed in this section.

SOFC

The following chemical reactions that took place generally in SOFC during power generation [6]

$$Anode: H_2 + O^{2-} \rightarrow H_2O + 2e^- \quad (1)$$

$$CO + O^{2-} \rightarrow CO_2 + 2e^- \quad (2)$$

$$Cathode: O_2 + 4e^- \rightarrow 2\,O^{2-} \quad (3)$$

In the current analysis, it is assumed that fuel reacts with H_2O and releases H_2 and CO. CO again reacts with H_2O in shift produces H_2. The heat required for reformer is supplied by the SOFC. The chemical reactions for different fuels are given below:

If Ethanol is the fuel based on Douvarttzides et al. [19], One mole of ethane releases six moles of H_2 and two moles of CO.

$$C_2H_5OH + 3H_2O \rightarrow 2CO + 6H_2 \quad (4)$$

The energy interactions of the cell require the evaluation of both the current and voltage. The reversible cell voltage, E, is defined by Haseli et al. [22] by considering Nernst equation is

$$E = E^0 + \frac{RT}{8F}\ln\left[\frac{P_{CH_4} \times P^2O_2}{P_{CO_2} \times P^2H_2O}\right] \quad (5)$$

Ideal voltage values for an intermediate temperature SOFC operating at 800^0 C and 1100^{0}C are 0.99V and 0.91V respectively[32].

The DC power produced by the SOFC is given [19] by

$$P_{ele,dc} = V_c \times j \times A_c \quad (6)$$

The actual cell voltage 'V_c' depends upon the operating parameters like the current density (j), operating pressure and temperature etc.

The rate of heat production due to irreversibilities is given by [1]

$$Q_{Gen,FC} = P_{ele,dc}[(1.25/V_C) - 1] \times 10^{-6} kW \quad (7)$$

The oxygen required for chemical reaction is normally supplied from air. The air flow is usually well above the stoichiometric amount, normally twice higher. If the stoichiometric ratio is λ[1], then mass flow rate of air usage is given by

$$m_{a,FC} = 3.57 \times 10^{-7} \times \lambda \times \frac{P_{ele,dc}}{Vc}\ kg/s \quad (8)$$

ExergyEvaluation[31]:

Thermal exergy

$$E_{x,th} = mC_p[(T - T_0) - T_0\ln(T/T_0)] \quad (9)$$

Mechanical exergy $=E_{x,m} = mRT_0 \ln(P/P_0)$ (10)

Chemicalexergy

$$E_{x,ch} = mRT_0 \sum x_i \ln(x_i/y_i) \quad (11)$$

Irreversibility in SOFC:

$$I_{SOFC} = T_0\left[\left\{(S_p)_4 - (S_p)_0\right\} - \{(S_a)_3 - (S_a)_0\} + \{(\Delta S)_{reaction}\}_0\right] \quad (12)$$

Irreversibility of the combustion reaction[32] isgiven by

$$T_0(\Delta S)_{rxn} = m_{ffc}(LHV)_f(\Phi - 1) \quad (13)$$

WhereΦ=(-ΔG/-ΔH)=(51840/50050)=1.035764 (14)

Byenergy balance [6]:

$$m_3h_3 + m_{ffc} \times U_f \times LHV + m_{ffc} \times (1 - U_f)h_{f,in} - P_{ele,dc} - m_4h_4 = 0 \quad (15)$$

By exergy balance [6]:

$$m_3\Psi_3 + m_{ffc} \times (\Psi_{fm} + \Psi_{ft}) + m_{ffc} \times \Psi_{ch,f} \times U_f - m_4\Psi_4 - P_{ele,dc} - E_{x.}D_{SOFC} = 0 \quad (16)$$

Exergyefficiency

$$\eta_{ex,FC} = \frac{P_{ele,dc}}{[m_{ffc}(\Psi_{fm}+\Psi_{ft})+m_{ffc}*U_f*\Psi_{ch,f}]-(m_4\Psi_4-m_3\Psi_3)} \quad (17)$$

Combustion Chamber

The products from the SOFC are further heated in the combustion chamber by supplying adequate quantity of fuel. The unburnt fuel in the SOFC is also burnt in the combustion chamber.

By energy balanceof Combustion Chamber:

$$(m_3 + U_f \times m_{ffc})h_4 + Q_{comb} - m_5 h_5 - Q_{loss} = 0 \quad (18)$$

Where $Q_{comb} = [m_{ffc} \times (1 - U_f) + m_{fcc}] \times LHV$ (19)

$$Q_{loss} = [m_{ffc} \times (1 - U_f) + m_{fcc}] \times (1 - \eta_{comb}) \times LHV \quad (20)$$

By exergy balance:

$$m_4\Psi_4 + m_{ffc} \times (1 - U_f)\Psi_{ch,f} + m_{fcc}(\Psi_{fm} + \Psi_{ft} + \Psi_{fch}) - m_5\Psi_5 - E_x D_{cc} = 0 \quad (21)$$

In the above equation, the irreversible heat source term is not considered, since it is assumed that ambient temperature (T_o) is equal to the sink temperature (T_{sink}).

Irreversibility in combustion chamber

$$I_{cc} = [\{(S_p)_5 - (S_p)_0\} - \{(S_a)_4 - (S_a)_0\} + \{(\Delta S)_{rxn}\}_0] \quad (22)$$

Where$(\Delta S)_{rxn} = T_0(\Delta S)_{reactants} =$
$m_{ffc} \times (LHV)_f(\Phi - 1)$ (23)

Exergyefficiency

$$\eta_{ex,cc} = \frac{m_5\Psi_5 - m_4\Psi_4}{m_{ffc}*(1-U_f)\Psi_{ch,f}+m_{fcc}(\Psi_{phf}+\Psi_{chf})} \quad (24)$$

Compressor

Irreversibility in the compressor is given by

$$I_{com} = T_0(S_2 - S_1) \quad (25)$$

Exergy efficiency=

$$\eta_{ex,comp} = \frac{m_1(\Psi_2-\Psi_1)}{m_1(h_2-h_1)} \quad (26)$$

Recuperator

Irreversibility in the Recuperator is given by

$$I_{Rec} = m_6(\Psi_6 - \Psi_7) - m_2(\Psi_3 - \Psi_2) \quad (27)$$

Exergyefficiency =

$$\eta_{ex,Rec} = \frac{m_2(\Psi_3-\Psi_2)}{m_6(\Psi_6-\Psi_7)} \quad (28)$$

Gas Turbine

Rate of exergy loss in the gas turbine is given by:

$$I_{GT} = m_5 \times T_0 \times (S_5 - S_6) \quad (29)$$

Exergyefficiency=$\eta_{ex,GT} = \frac{P_{gt}}{m_5(\Psi_5-\Psi_6)}$ (30)

Performance of the plant

Net power developed by SOFC stack

$$P_{FC,AC} = \eta_{invert} \times P_{ele,dc} \quad (31)$$

Net power developed by the gas turbine

$$P_{Gen} = \eta_{Gen} \times P_{gt} \quad (32)$$

Total net power developed by the system

$$P_{net} = P_{FC,AC} + P_{Gen} \quad (33)$$

The total heat supplied to the system

$$Q_{tot} = m_{ffc} \times U_f \times LHV_{CH4} + Q_{comb} \quad (34)$$

The total thermal efficiency of the cycle =

$$\eta_{th,cycle} = \frac{P_{net}}{Q_{tot}} \quad (35)$$

The exergy efficiency of the cycle

$$\eta_{ex\ cyc} = P_{net}/m_f(\Psi_{fm} + \Psi_{ft} + \Psi_{f,ch}) \quad (36)$$

3. RESULTS AND DISCUSSION

The thermodynamic analysis of GT-SOFC combined cycle has been carried out and the results obtained by varying the cycle parameters have been plotted.

Figure 2 and figure 3 show the variation of cycle efficiency and exergy efficiency with variation of the pressure ratio. The thermal and exergy efficiencies are increasing with pressure ratio up to 9, and then start decreasing. When the methane, natural gas, coal gas and ethanol are used as fuels, at the optimum pressure ratio 9, the total thermal and the exergy efficiencies are found to be 61.36% and 55.06% respectively. At higher pressure ratio the power output from the fuel cell increases due to higher cell e.m.f. The difference between enthalpy of reaction and cell electrical output is the heat energy available for raising the temperatures of input fuel gas and air in SOFC up to the cell operating temperature. The greater the heat for raising the temperature of gas and air streams, the more is the exergy loss. With higher pressure ratio, this heating decreases as the difference between SOFC operating temperature and the temperature of air to the SOFC decreases. Hence, the exergy loss decreases and exergetic efficiency increases as shown Figure 4 depicts the variation of exergy destruction with the increase in pressure ratio due to increase irreversibilities in all the components particularly in combustion chamber and SOFC. At higher pressure ratio, electrochemical reaction in the SOFC increases resulting in less combustibles for combustion in Combustion Chamber. Hence, the exergy destruction due to chemical reaction in Combustion Chamber decreases at higher pressure ratio. As a result, the exergy loss decreases and exergetic efficiency increases for Combustion Chamber with higher pressure ratio. With higher pressure ratio, the temperature of the exhaust gas form the gas turbine decreases. Hence, at high pressure ratio, heat transfer in the recuperator occurs at low temperature difference. This gives the lower exergy loss at high pressure ratio in the recuperator. Figure 5 presnets the variation of net power output from the gas turbine with the pressure ratio. The max.net power output is 898.19kW for the optimum pressureratio of '9'.

Figure 6 shows the variation of thermal efficiency with the turbine inlet temperature. The efficiencies are increasing with increase in TIT, It is due to utilization of exergy of unburnt fuel from the fuel cell and the additional supply of fuel in the combustion chamber. Figure 7 presents the variation of exergy destruction with the turbine inlet temperature. The exergy destruction and net power out put from the turbine both are increasing with increase in TIT.This is due to high temperature of the working fluid in the gas turbine.Power output of about 30-50% of SOFC power can be obtained from the generator. The increase in power output requires higher fuel flow rate which leads to the increase in total exergy destruction. So power output from turbine can be controlled by adjusting Air fuel ratio.

The effect of increase in ambient temperature on the variation of efficiency is shown in the Figure 8.The cycle efficiency is decreased with the increase in ambient temperature, due to higher power requirements in the compressor. The net power output from the gas turbine is decreasing by 25 kW,for every 5°C increase in the ambient temperature. The maximum exergy destruction occurs in the SOFC and combustion chamber irrespective of the type of fuel used.This is due to highest temperature of the working fluid, chemical reactions and a small pressure drop. At the optimum pressure ratio 9,the maximum exergy destruction(1838kW) occurs for the fuel ethanol followed by diesel (1594kW).

Table: 2 Performance comparison of SOFC-GT hybrid system

	Ethanol	Diesel
Thermal efficiency	61.36 %	70.72 %
Exergy efficiency	55.14 %	66.76 %
Exergy Destruction	1838 kW	1594 kW

4. CONCLUSION

Combined cycle power plants have higher efficiency than those of recuperated gas turbine and atmospheric fuel cell, because exergy losses of combustion are made much smaller. An increase in pressure ratio results in lower rate of exergy destruction of the plant. An increase in Turbine inlet temperature and ambient temperature results in higher rate of exergy destruction of the plant. A certain pressure ratio gives the highest generation efficiency, but its variation near the optimum point does not lead to a remarkable difference. The

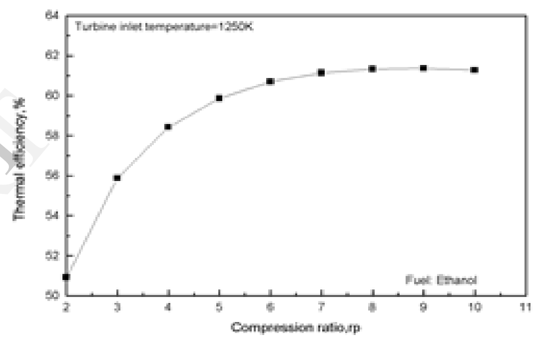

Figure 2 Thermal efficiency Vs Pressure ratio

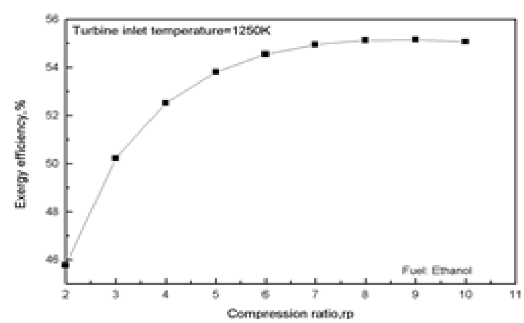

Figure 3 Exergy efficiency Vs Pressure ratio

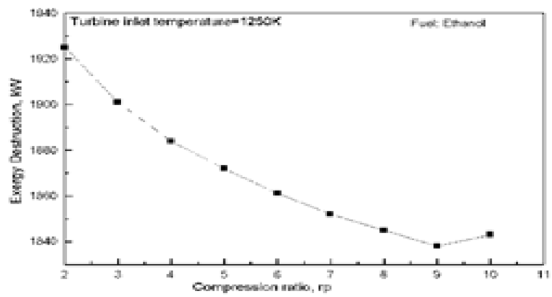

Figure 4 Exergy Destruction Vs Pressure ratio

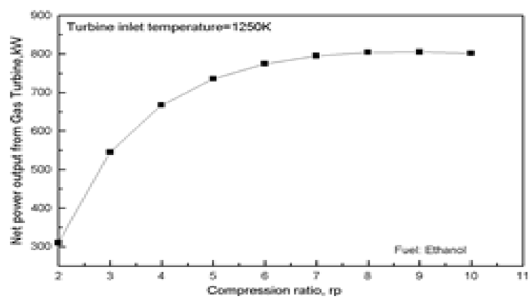

Figure 5 Net power output from gas turbine Vs Pressure ratio

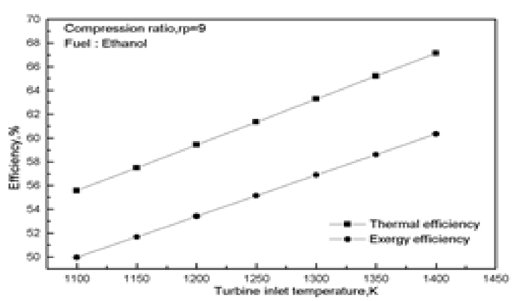

Figure 6 Thermal efficiency Vs Turbine inlet temperature

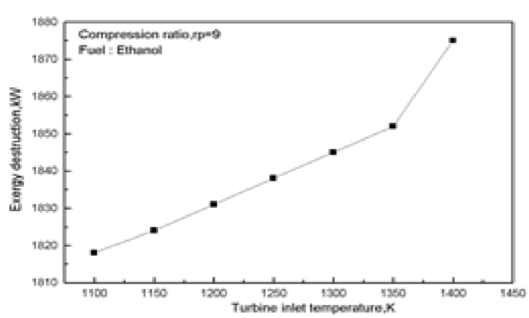

Figure 7 Exergy Destruction Vs Turbine inlet temperature

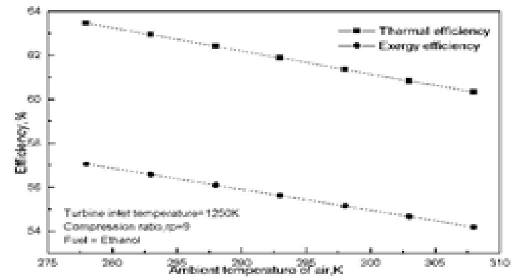

Figure 8 Thermal efficiency Vs Ambient temperature

exergy destruction in SOFC is maximum, though it is an efficient device. Exergy analysis of each component provides better understanding of losses at various states of the system. It has been observed that the better energy and exergy efficiencies can be obtained when the diesel is used as fuel when compared to ethanol. Diesel fueled fuel cell – gas turbine hybrid systems are more clean and efficient energy solutions compared to internal combustion engines for electric power generation. For this system the energy and exergy efficiencies are obtained as 70.72 % and 66.76% respectively.

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