International Journal of Engineering Research-Online
A Peer Reviewed International Journal
Email:editorijoer@gmail.com http://www.ijoer.in

Vol.4., Issue.1., 2016
(Jan-Feb)

RESEARCH ARTICLE

ISSN: 2321-7758

PERFORMANCE DETERIORATION OF GAS TURBINE: SURVEY AND CHALLENGES AHEAD

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ABSTRACT

Performance deterioration of gas turbine has a direct effect on the overall profitability of power plants. Therefore, it is essential to grasp the causes, the measurements of performance deterioration of gas turbine and regain the lost performance. In this paper, we aim to provide a thermodynamic model on a single shaft industrial gas turbine to identify and analyze the most important underlying factors (i.e., faults) that have a significant effect on the performance deterioration and measure it through a proposed matching algorithm. These measurements done according to the compressor discharge temperature, compressor pressure ratio, inlet turbine temperature, fuel mass flow rate and engine loading order absorb different physical phenomena occurring in the engine. The results of proposed thermodynamic model compared against the real engine model and have proven its accuracy. The experimental results of matching algorithm have proven that, the power output decreased linearly with increased degradation performance of compressor efficiency, turbine efficiency and air mass flow rate. In addition, the specific fuel consumption rate increased linearly with increased degradation performance of combustion efficiency. Also, the degradation performance of air mass flow rate is strongly influence on decreasing compressor discharge temperature, inlet turbine temperature and compressor pressure ratio.

Keywords— Gas Turbine, Performance deterioration, Fouling, Component Characteristics Map, Turbine.

Nomenclature

H Specific Enthalpy [J/kg]
$ma^{\bullet}$ Air mass flow rate[kg/s]
$m^{\bullet}$ Mass flow rate [kg/s]
$m^{\bullet}{}_{f}$ Fuel mass flow rate
T1 Compressor Inlet temperature
T2 Compressor discharge temperature
T3 Inlet turbine temperature
T4 Exhaust temperature
P1 Atmospheric pressure
P2 Compressor discharge pressure
P3 Turbine Inlet pressure
P4 Pressure out turbine
πc Compressor pressure ratio=$(\frac{P2}{P1})$
πt Turbine pressure ratio= $(\frac{P4}{P3})$
K The ratio of specific heats of the gas, k=1.4 with air or 1,34with (air and gas).
PR Pressure ratio

$PR_{design\ ,model}$ Pressure ratio of design point map values of scaled components
$PR_{design\ ,map}$ Pressure ratio of design point map values of original components
PR_{map} Pressure ratio of arbitrary map values
$m^{\bullet}_{map}$ Mass flow rate of design point map values of scaled components
ηIsentropic efficiency
$\eta_{designmodel}$ Isentropic efficiency of design point map values of scaled components
$\eta_{designmap}$ Isentropic efficiency of design point map values of original components
η_{map} Isentropic efficiency of arbitrary map values
$m^{\bullet}_{designmodel}$ Mass flow rate of design point map values of scaled components
$m^{\bullet}_{designmap}$ Mass flow rate of design point map values of original components
H_1Compressor inlet enthalpy
H_2Compressor discharge enthalpy
H_3Turbine inlet enthalpy
H_4Turbine discharge enthalpy
$\Delta T1,2$Deferential temperature
$\Delta T3,4$ Deferential temperature
Υ ratio of specific heats = cp /cv , γ=1.4
ΥcSpecific heats ratio for compressor
Υt Specific heats ratio for turbine,
Cp Specific heat of air at constant pressure
Cv Specific heat of air at constant volume
HcCompressor isentropic efficiency
η_b Isentropic efficiency ofthe burn
ηtTurbine isentropic efficiency
$m^{\bullet}_3$Turbine mass flow rate
HVHeating value (is the amount of heat released during the combustion of a specified amount of it)
N_tTurbine Rotational speed
N_cCompressor rotational speed.
L Engine load

INTRODUCTION

The Gas Turbine (GT) has become an important, widespread, and reliable device in the field of power generation. Gas turbine is an internal combustion engine which uses the gaseous energy of air to convert chemical energy of fuel to mechanical energy [1]. A simple gas turbine engine consists of a compressor, a combustion chamber and a turbine that is directly connected to a generator [2] as shown in Fig. 1.

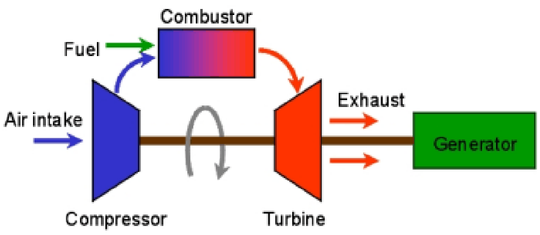

Fig. 1Gas Turbine Engine.

The performance of industrial gas turbine is considered as an important factor in many disadvantageous environments around the world. Deterioration in the performance of gas turbines has been done during the operation process of GT. It leads to reduce both the capacity and thermal efficiency factors. Loss of capacity leads to loss in production, and loss in thermal efficiency can cause increasing in the fuel consumption that leads to higher fuel costs. As a result, it causes a reduction in the overall profits.

Performance deterioration is considered as a combination of temporary and permanent deterioration form [3]. In the temporary form (i.e., recoverable deterioration), the performance loss is resulting from contaminant buildup such as fouling on engine surfaces exposed to the gas path. A majority of these contaminants can be removed by cleaning the affected surfaces to recover the performance lost. The permanent form (i.e., non-recoverable deterioration) is caused by physical damage resulting from erosion, corrosion and some fouling. The non-recoverable performance deterioration may only be recovered after a complete engine overhaul. In [4], the engine performance deterioration categorized into three different types which are, recoverable with cleaning or washing, non-recoverable with cleaning/washing and permanent that will not be affected by cleaning or washing which will remain and perhaps get worse with time.

The recoverable deterioration [5] is usually associated with compressor fouling and can be partially rectified by water washing or by mechanically cleaning the compressor blades and vanes after opening the unit. With the continuity of cleaning or washing, some deposits will remain stuck on the component's surface, which leads to the deterioration in the performance and the overall efficiency of the component.

Therefore, it has a great significance to identify and analyze the gas turbine engine performance deterioration factors in order to reduce the cost maintenance operation. It is the main contribution of this paper to present an effective mathematical thermodynamic model based on thermodynamic principle and alternative characteristic maps of main engine components. The model aimed to measure the performance deterioration of industrial gas turbine according to some faults and compared with real data to ensure its accuracy and efficiency.

The reminder of the paper is structured as follow. In the following section, we present a literature review on the performance deteriorations in industrial gas turbine, and then we identify a mathematical thermodynamic model of gas turbine engine. Then, we develop an effective model for measuring the performance of gas turbine with respect to different faults associated with a matching proposed algorithm. Building upon this; an experimental results of the proposed algorithm presented and compared with real data to prove the accuracy of proposed model. At last, we conclude the paper by discussing the most important challenges of our proposed model algorithm and proposing directions for future research.

LITERATRURE REVIEW

Recently, measuring the performance of gas turbine has received a significant amount of attention. There are a lot of research papers that concerned the subject of performance deteriorations in industrial gas turbine either in a mathematical way or focus on a specific subset of deterioration factors. The understanding of the factors that cause the performance deterioration is a matter of interest. Among these factors are:

- Air-borne contaminants that can be divided into hard particles and soft particles [4]. The hard particles such as dust, dirt, sand, rust, carbon particles and ash that cause erosion and fouling while the soft particles such as oil, unburned hydrocarbons, soot, air-borne industrial chemicals and air-borne salts that also cause fouling.
- Fouling that is caused by adherence of a particular contaminant to the gas turbine engine. This leads to degradation of flow capacity and efficiency. Fouling can occur in both compressor (i.e., compressor fouling) and turbine (i.e., turbine fouling). A compressor fouling is caused by contaminants that enter the compressor with the inlet air while the contaminants that cause turbine fouling enters the turbine with the inlet air, cooling air and fuel [4]. All compressors are liable to fouling. The effect of fouling on the performance of gas turbine depends on compressor design, airfoil surface smoothness or coating, type and condition of the air-borne contaminants, the site environment, and the climatic conditions [3]. Turbine fouling depends on the ability of the contaminants to reach the turbine and stick to the gas path surfaces [6]. Cleaning the gas turbine engine flow path surfaces is an important part to restore these surfaces to their initial condition. There are many methods to restore the compressor components to their initial new condition such as manual cleaning, dry cleaning, and washing. The selection of the most effective method depends on the type and condition of the contamination [4]. On the other hand, cleaning the hot end components (e.g., combustion system, turbine, and exhaust diffuser) is more difficult to accomplish.
- Filtration System of gas turbine which responsible for removing particles, such as dirt and dust from the compressor inlet flow and protecting it against compressor fouling, erosion and corrosion [7].
- Erosion is considered as the process of removing material from a surface which occurred as the result of some factors such as fly ash, water droplets and maintenance tools among the gas turbine components [7]. The authors in [8] mentioned that, the compressor is more prone to erosion.
- Corrosion is considered as the process of losing substance from flow path surfaces that is caused by the chemical reaction between surface components and certain contaminants which enter the gas

turbine with the inlet air, fuel, or injected water such as, salts and mineral acids that lead to increases surface roughness [3] [8].

The above factors are considered as the most important and effective causes (i.e., faults) of performance deterioration in gas turbines that can occur during operation. The effect of these detectable faults may change different engine gas path variables. The authors in [9] mentioned that, deterioration has affect on relevant factors such as the power output and specific fuel consumption.

These physical faults lead to the change in gas turbine performance that is measured by flow capacity and efficiency of components. This change is noticeable in engine parameter such as temperature, pressure and fuel flow rate. These measurements can be used to detect and isolate components faults [10]. The effect of faults on the gas turbine performance deterioration is shown in Fig. 2.

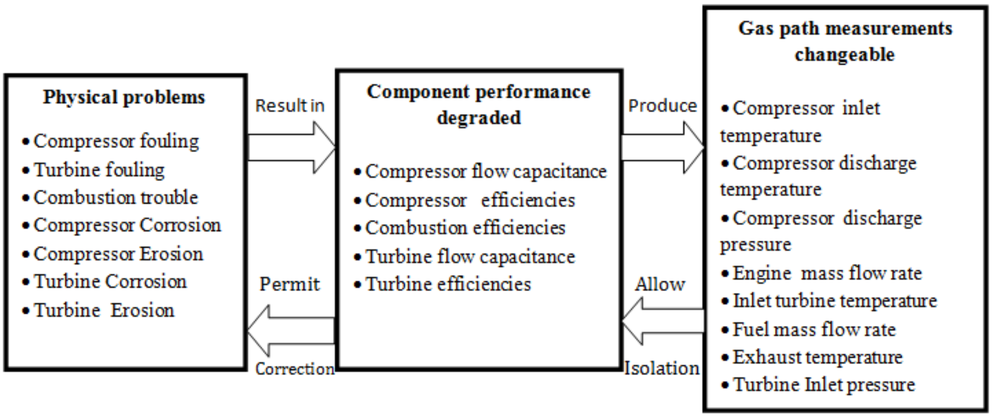

Fig. 2 GT performance degradation scheme.

The authors in [9] mentioned many approaches for monitoring gas turbines and fault diagnoses, such as performance analysis, x-ray checks, vibration monitoring, noise monitoring, and others. Performance analysis is one of the most powerful approaches among them in which, analysis of engine gas path variables provide effective information about the deterioration of gas path components.

Performing a component analysis has a twofold advantage. The first is that, the performance of mechanical devices deteriorating significantly due to consumption over time. The second is that, one or more of the deterioration of the basic components such as compressor or turbine occurred because of fouling, corrosion and erosion. So, changes in a component can modify its performance and has a significant effect on the overall behavior of the engine.

The performance of major engine components is based on component characteristics maps. These maps contain confidential data that are usually obtained from analytical methods. It is not easy to obtain these maps from gas turbine manufacturer, so in order to overcome this, there is a design point performance data taken from components maps (e.g., compressor and turbine maps). These maps can be obtained from GAS-TURB program [11] that scales to match the design point of compressor and turbine for studying and measuring gas turbine engine performance [12].

Under the components characteristics maps, the relation between parameters such as compressor flow rate, pressure and non-dimensional speed is called a compressor characteristics map while the relation between turbine flow rate, pressure and non-dimensional speed is called a turbine characteristics map. Any change in the component performance has an indirect effect in the corresponding maps that measure the efficiency of parameters. Measuring the deterioration of any component can be obtained from the analysis of changes in the measurements.

Some researches interested in gas turbine performance evaluations using software modeling which converts the parameters that have a significant effect on the performance of the gas turbine to a code that predict errors before they can occur [13][14][15].

One of the most economical solutions is mathematical modeling by using computational techniques. The authors in [16] presented a computer program that satisfied matching conditions analytically between various gas turbine components to produce an equilibrium running line. On the other hand, the authors in [17] compared a model that derived from an actual engine data with a model that constructed from the theoretical relationship between the engine data. The authors in [18] designed a multiple Bayesian models of various fault situations are implemented in one hierarchical model to maintain the generality and the accuracy together. Early detection of faults considered a helpful tool in maintenance field [19] to take corrective actions in good time [20].

Measuring the engine performance by checking the simulation capabilities of the analytical model is an important thing; therefore the results of designing a model of a single-shaft gas turbine were compared with design working parameters of a single shaft 60 MW commercial gas turbine [21]. The authors in [22] developed a Simulink model to calculate the off-design running point for a single shaft power generation gas turbine engine. The off design calculations comprised two models, the first is the operation during the engine starting (i.e., from 65% to 100% speed, no load) while the second is the engine operation during the loading (i.e., at constant speed of 100%). In this paper, we measure the engine parameters deterioration with changeable temperature of proposed model against real model of single spool 9EA(125 MW) gas turbine engine during the loading (i.e., at constant speed of 100%).

Therefore, a simulated model to identify and analyze the most important underlying faults which cause component deterioration by using a map modifier implemented in Matlab. Build upon this, measure the effect of component deterioration, the causes, and measurements on the overall performance deterioration of gas turbine can be integrated in the proposed model.

Mathematical model of GT engine

In order to design and operate a gas turbine, a simulate engine performance required by constructing a mathematical model that is able to absorb different physical phenomena occurring in engine. According to the main purpose of gas turbine is producing power by converting heat into work. The heat is achieved by burning fuel in the combustion system. Thus the best way for performance analysis of a gas turbine is achieved by applying the principles of thermodynamics process and map scaling.

Thermodynamic process

It is necessary to determine the thermodynamic properties of the working media at any point through the path of gases. These properties are enthalpy (H), gas constant (R) and specific heat at constant pressure (CP).The thermodynamic properties for air or fuel are given as functions of temperature according to formula (1) and (2) (i.e., adapted from NASA[23]).

$$\frac{CP(t)}{R} = a_1T^{-2} + a_2T^{-1} + a_3 + a_4T + a_5T^2 + a_6T^3 + a_7T^4 \quad (1)$$

$$\frac{H(t)}{R} = -a_1T^{-1} + a_2\ln(T) + a_3T + \frac{a_4}{2}T^2 + \frac{a_5}{3}T^3 + \frac{a_6}{4}T^4 + \frac{a_7}{5}T^5 + b1 \quad (2)$$

Where a's are temperature coefficients and b's integration constants. The thermodynamic working cycle of a gas turbine engine is known as the Brayton Cycle[24]. It is a cycle that describes how gas turbines operate. The basic idea behind the Brayton Cycle is to extract energy from flowing air and fuel to generate usable work which can be used to power many engines. The most basic steps in extracting energy is compression of flowing air, combustion, and then expansion of that air to create work. The importance of the Brayton Cycle is tremendous due to the fact it is the backbone in driving many engines. Fig.3 shows an ideal Brayton Cycle, which represents the basic three stages of gas turbine process.

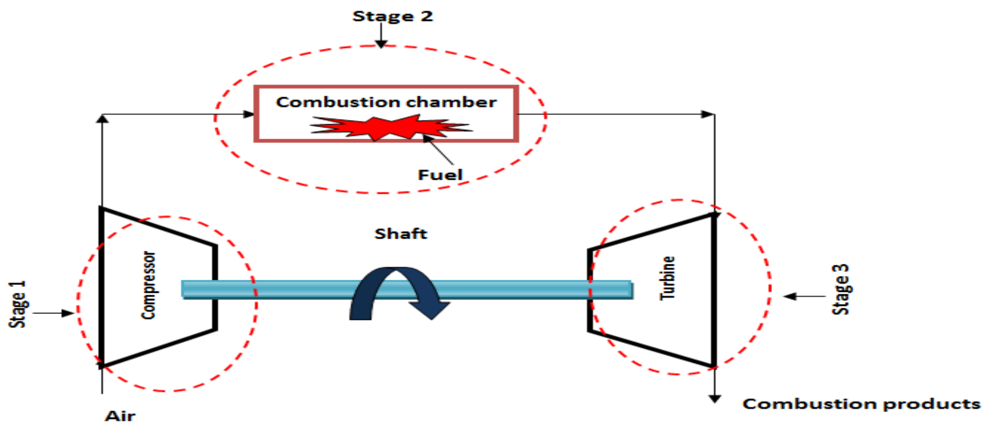

Fig. 3 Ideal Brayton Cycle.

- *Stage 1:* represents a compression process, where in the gas turbine plant layout, Itoccurs in compressor. The compressor power($Power_c$) [23] can be expressed by equation (3).

  $Power_c = ma^{\bullet}{}_1(H_2 - H_1)$ (3)

  Where, $ma^{\bullet}{}_1$is air mass flow rate,$H_1$is Compressor inlet enthalpy, $H_2$is Compressor discharge enthalpy. While the compressor discharge temperature ($T2$)[25] for an isentropiccompression is given by equation (4)

  $T2 = T1 * \left(\frac{P2}{P1}\right)^{\frac{k-1}{k}}$ (4)

  Where $T1$is compressor inlet temperature, $P1$ is an atmospheric pressure,$P2$is a compressor discharge pressure and $K$is the ratio of specific heats of the gas.
- *Stage 2:* represents a combustion process, where in the gas turbine plant layout the combustion products depend on the heat that is released when the fuel and air are burned. The use of hydrocarbon fuels is widespread in gas turbines. Liquid fuels such as kerosene, or gaseous fuels such as natural gas, are examples and the use of natural gas is becoming increasingly common in industrial gas turbines. The amount of heat input is often referstothe net thermal input. For methane as fuel, this reaction can be written as in equation (5).

  $CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O + HEAT$(5)
- *Stage 3*:representsan expansion process that occurs in turbine. The turbine power($Power_t$)[23] can be expressed by equation(6)

  $Power_t = (ma^{\bullet}{}_2 + m_f)(H_3 - H_4)$(6)

Where, m_f is fuel mass flow rate,$H_3$is turbine inlet enthalpy,H_4 is turbine discharge enthalpy, the exhaust temperature T4 [25] for an isentropic compression is given by equation (7).

$T4 = T3 * (\frac{P4}{P3})^{\frac{k-1}{k}}$(7)

Where,$T3$ is Inlet turbine temperature, $P4$ is pressure out turbine and $P3$ is turbine Inlet pressure.

Map Scaling

Accessing the characteristics of gas turbine components in different environmental and operational conditions are very difficult because these technical data is very expensive to obtain. Therefore, engineers and users measure the performance of the engine components and utilize the engine components' characteristics through performance calculation techniques such as scaling method, stage-stacking method, and blade element for compressor method. The scaling method is considered as an easiest way to obtain.

In this research, we use a traditional scaling method. It is a way to derive a scaled component maps (i.e., pressure ratio(PR), air math flow rate ($ma^{\bullet}$)and efficiency (η))from the original one in which the scaling factors of the derived maps obtained from the comparison between a design data point of original known performance map and a new design point. These scaled maps can be obtained by multiplying the derived scaling component factors (PR_{design} ,$ma^{\bullet}{}_{design}$ *and* η_{design}) to off-design point data (PR_{map} ,$ma^{\bullet}{}_{map}$,η_{map})of the original performance maps by using the following equations associated with each component in both compressor and turbine map scaling [12].

$$PR_{model} = PR_{design} * (PR_{map} - 1) \quad (8)$$

$$ma^{\bullet}_{model} = ma^{\bullet}_{design} * (ma^{\bullet}_{map}) \quad (9)$$

$$\eta_{model} = \eta_{design} * (\eta_{map}) \quad (10)$$

Where, $PR_{design} = \left[\frac{PR_{design,model} - 1}{PR_{design,map} - 1}\right]$, $ma^{\bullet}_{design} = \left[\frac{ma^{\bullet}_{design\ model}}{ma^{\bullet}_{design\ map}}\right]$ and $\eta_{design} = \left[\frac{\eta_{design\ model}}{\eta_{design\ map}}\right]$

Compressor and turbine map scaling

Compressor maps are important, since they are an integral part of predicting the performance of a gas turbine engine. Characteristics map of the axial compressor and turbine are taken from GasTurb12 program [26]and scaled to match the design point of the compressor and turbine**.** The following basic steps for obtaining a compressor or turbine map scaling.

*Step 1:*specify a design point for the model from the original map [5].

Step2: choose a design point for the original map that has a high efficiency or that is given in the original map hint.

Step 3: generate a new map by using map scaling equations (8),(9) and (10) to generate the new compressor or turbine map.

A way to simulate engine component deterioration (fouling, corrosion, etc.) is to specify the associated effects on component performance degradation in the model. One method to represent component deterioration is using 'map modifiers' that change the performance simulated in a Matlab code (m.file). In which, η and $ma^{\bullet}$ are called component condition parameters. The basic idea behind the model is that, component characteristics (e.g. compressor map) are allowed to be changed through the introduction of appropriate modification factors. The values of these factors in the model are determined by requiring the available engine performance data and matched by the engine model results.

The corrected factor $(C.F)$ for each component parameter (x) is defined by following general relation.

$$C.F = \frac{x_{real}}{x_{ref}} \quad (11)$$

Each compressor and turbine employs two corrected factors, one related to flow capacity $(C.F_{ma^{\bullet}})$ and the other related to efficiency $(C.F_{\eta})$[8]. The flow capacity factor and the efficiency factor can be presented by equation (12) and (13) respectively.

$$C.F_{ma^{\bullet}} = \frac{ma^{\bullet}_{real}}{ma^{\bullet}_{ref}} \quad (12)$$

$$C.F_{\eta} = \frac{\eta_{real}}{\eta_{ref}} \quad (13)$$

Thermodynamic cycle calculations

Each compressor or turbine has a certain design point where the rotational speed *(N),* compressor pressure ratio (πc), and air mass flow rate ($ma^{\bullet}$) are specified. However, it is requested for these modules to operate efficiently over the complete range of speed and power output for a power plant. These conditions are identified as the off-design conditions.

The main objective of the design calculations is to calculate all thermodynamics properties (e.g., *P, T, H,...*) at all engine points. The fuel flow rate, the power output and some other properties are used for both compressor and turbine map scaling to achieve off design calculations. By using the ambient condition ($T1$, *P1*), all the design properties are calculated through the thermodynamic cycle calculations.

Compressor process

The overall performance of gas turbines is dominated by the compressor behavior; therefore modeling gas turbine performance should always be primarily based on actual compressor characteristics. Some simplified methods have been suggested to approximate the compressor behavior outside design conditions. However, without the information of compressor geometry, some vital performance data will be lost.

For this reason, as shown in Fig.4, set of inputs (i.e., from the known properties at inlet$P_1, T_1, H_1, ma^{\bullet}_1, etc.$) and operating point of the compressor are mapped to set of outputs [25] (e.g., $P_2, T_2, H_2, ma^{\bullet}_2$, etc.) to determine the air properties at compressor discharge through processing done according to the knowing compressor map (e.g., $ma^{\bullet}, PR, \eta$) by using the following relation.

$$\Delta T_{1,2} = \frac{T1}{\eta c}\left[\left(\frac{P1}{P2}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] \quad (14)$$

Where $\Delta T_{1,2}$is deferential temperature,γ is ratio of specific heats,ηc is a compressor isentropic efficiency.

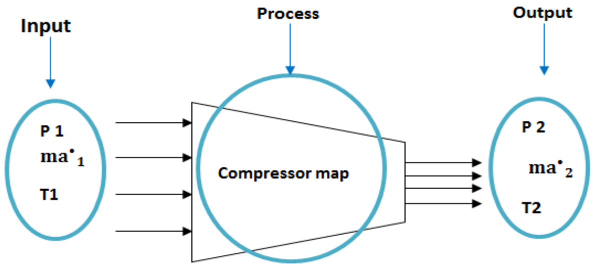

Fig. 4 Compressor process .

Combustion chamber process

The function of the combustor as shown in Fig. 5is the process to burn fuel with compressed air discharged from the compressor with minimum pressure drop. The flow through the combustor is assumed to be steady, one dimensional, where gases do not perform any work. Applying energy balance to the combustion process will lead to the following relation [27].

$$ma^{\bullet}_2 * H_2 + \eta_b * m^{\bullet}_f * HV = (ma^{\bullet}_2 + m^{\bullet}_f) * H_3 \quad (15)$$

Where,$m^{\bullet}_f$ is Fuel mass flow rate,$\eta_b$is an Isentropic efficiency of the burn,$HV$is Heating value,H_3 is Turbine inlet enthalpy .

The actual Combustion temperature T_3 is determined fromH3. A small pressure drop may occur through the combustor, which considered being 4% of the total pressure at combustor inlet($\Delta p_{c.c}$) in the design load.

$$\Delta p_{c.c} = 0.04P_2 \quad (16)$$

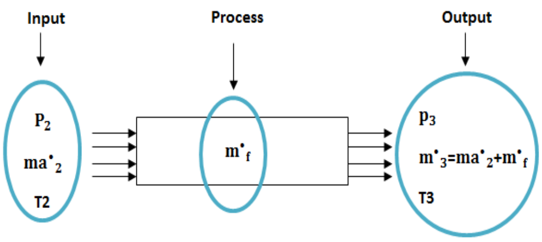

Fig. 5Combustion chamber process.

Turbine process

The turbine is used to extract energy from flowing stream of gas. As shown in Fig. 6, both total pressure and temperature drop through this process and the flow is considered to be adiabatic as heat exchange across the turbine is ignored. It is required to determine the air properties (e.g., P_4, T_4, H_4, etc) at turbine exit as an output of such processfrom the set of input known properties (e.g., P_3, T_3, H_3, etc) at turbine inlet[27] according to equation (17) and respectively the deferential temperature $\Delta T3{,}4$is computed according to equation (18).

$$T3=\left(\frac{T1}{\eta t * \eta c}\right)\left(\frac{ma^{\bullet}_2}{m^{\bullet}_3}\right)\left(\frac{cp1}{cp3}\right)\left(\frac{\left(\frac{P1}{P2}\right)^{\frac{\gamma c-1}{\gamma c}}-1}{1-\left(\frac{P4}{P3}\right)^{\frac{\gamma t-1}{\gamma t}}}\right) \quad (17)$$

Where,$T3$ isInlet turbine temperature,ηc is compressor isentropic efficiency andηt is Turbine isentropic efficiency.

$$\Delta T3{,}4 = \eta t * T3\left[1 - \left(\frac{1}{\frac{P3}{P4}}\right)^{\frac{\gamma t-1}{\gamma t}}\right] \quad (18)$$

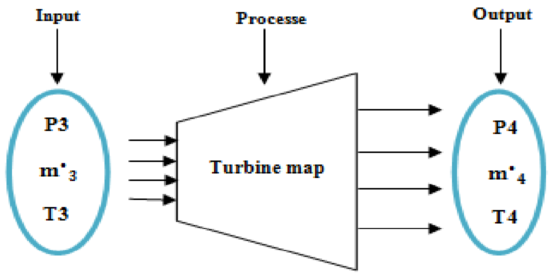

Fig. 6Turbine process.

Proposed Matching Algorithm

In this paper, we have considered a single-shaft engine in which a list of frequent and common faults is selected to measure the performance of an industrial gas turbine. Therefore, the faulty conditions represent realistic conditions usual in the industrial gas turbine engines distributed on the main components of the engine (i.e., compressor, combustion chamber and turbine) to include the usual deterioration of engine performance. Table 1 lists the most frequent faults with different levels of occurrence for each fault according to the range of degradation (i.e., fault level).

Table 1 List of frequent faults.

Fault no.	Description	Range of degradation
F1	Axial compressor efficiency decreased (C.E)	2-6 %
F2	Axial Turbine efficiency decreased (T.E)	1-4 %
F3	Air Mass flow	0.3-6.3 %

	decreased (M.R)	
F4	Combustion efficiency decreased (COM.E)	2-6 %
F5	Air filter blocked (FILT.BLOCK)	1-2 %

The matching means the interplay of the engine geometry and engine parameters. It is not only a matching between a turbine and driven compressor but also,it is a global synchronization of different components of GT and engine parameters. So, in this paper, we determine the engine parameters and study how the gas path measurements changeable according to engine component deterioration with different ambient temperatures in which, a set of constraints should be satisfied as listed below.

Constraint 1: the mass continuity$m^{\bullet}_{f}$ between compressor *(*$ma^{\bullet}_{2}$*)* and turbine *(*$m^{\bullet}_{3}$*)* should be determined by the following relation:$m^{\bullet}_{3}$=$ma^{\bullet}_{2}$+$m^{\bullet}_{f}$

*Constraint 2:*the power balance ($load$) between compressor *(*$Power_c$*)*and turbine *(*$Power_t$*)* should be computed according to the following relation:

$$load = Power_t - Power_c$$

Constraint 3: the speed of turbineN_t and the speed of compressorN_c is constant at 100% where, $N_t = N_c = 3000\ Rpm$

*Constraint 4:*the pressure balance$\Delta p_{c.c}$ between compressor ($p2$) and turbine ($p3$)should be computed according to the following relation: $P_2 = \Delta p_{c.c} + P_3$

Constraint 5: The exhaust temperature(T_{ex}) should be equal the reference temperature T_{ref} [5] i.e. $T_{ex} = T_{ref} = 838\ K$

The procedure that describes the proposed matching algorithm illustrated below with a flowchart presented in Fig. 7.

Input: A set of input parameters at the initialization include the inlet condition$P1 = 101320PAR, T1 = 288\ K$of the air properties and reference exhaust temperature T_{ref} *=838 k,*L_{max} *=140MW,*L_{min} *=70 MW,* $N = 3000\ RPM$

Output: A set of measurement parameters can be obtained as compressor discharge temperature (T2), compressor discharge pressure ($P2$), engine mass flow rate ($m^{\bullet}$), inlet turbine temperature ($T3$), fuel mass flow rate ($m^{\bullet}_{f}$), engine load (L) and filter differential pressure (Δp).

The algorithm includes the following processing basic steps:

Step 1: Modify the component map according to Equations (12) and (13).

Step 2: Set L_{max} *=130 MW,* L_{min} *=80 MW* according to the gas turbine manualand assume $load_{o.p} = \left(\frac{L_{max} + L_{min}}{2}\right)$ to apply constraint 2

Step3: Let $\frac{N}{\sqrt{T1}} = 100\%$and apply constraint 3. Assume the compressor operating point$C_{o.p}$ is at middle of highest $C_{h.p}$ and lowest point$C_{l.p}$ in the series of selected speed points $C_{o.p} = \left(\frac{C_{l.p} + C_{h.p}}{2}\right)$. As the series has 14 points so, $C_{h.p} = 14$and$C_{l.p} = 1$. At the first iteration, the compressor pressure ratio, efficiency and corrected mass flow rate can be obtained.

Step 4: Calculate $T2 = T1 + \frac{T1}{\eta c}\left[\left(\frac{P1}{P2}\right)^{\frac{\Upsilon-1}{\Upsilon}} - 1\right]$ according to equation (4) and $H2 = f(T2)$

Step 5: Set $T3max = 1200c$ or *1473K*and $T3min = T2$, then assume*T3a*=$\left[\frac{T3max + T3min}{2}\right]$

Step 6: Calculate *H3=f (T3a),*$m^{\bullet}_{f}$ =$\left[\frac{ma\,(H3-H2)}{HV*\eta b-H3}\right]$and $m^{\bullet}_{3}$*= (*$ma^{\bullet}_{2}$*+*$m^{\bullet}_{f}$*)* according to constrain number 1.

Step 7: Calculate $\frac{N}{\sqrt{T3a}}$ and use $m^{\bullet}_{3}$to get turbine pressure ratio ($p4$) and efficiency

Step8: Calculate $Cp1 = f\ (T1)$ and $Cp3 = f\ (T3)$

Step9: Calculate *T3b*

$$= \left(\frac{load + ma^{\bullet}_{2} * cp1 * \frac{To1}{\eta c}\left[\left(\frac{Po1}{Po2}\right)^{\frac{\Upsilon-1}{\Upsilon}} - 1\right]}{m^{\bullet}_{3} * cp3 * \eta t * \left[1 - \left(\frac{1}{\frac{Po3}{Po4}}\right)^{\frac{\Upsilon t-1}{\Upsilon t}}\right]} \right)$$

Step 10: Check the Turbine inlet temperature

If ($[T3a - T3b] \approx 0$), then it is correct, go step 11

Else if $[T3a - T3b] \prec 0$ *set T3min= T3a* and go to step 5(i.e.,*T3a decreased*)

Else set *T3max= T3a* and repeat from step 5(i.e.,*T3a increased*)

Step 11:Apply constrain 5 and calculate $T4 = T3 + \eta t * T3 \left[1 - \left(\frac{1}{\frac{P3}{P4}}\right)^{\frac{\gamma t-1}{\gamma t}}\right]$according to Equation (7)

Step 12: Set constraint 4 and compute $\Delta p_{err} = \Delta p_c - \Delta p_{CC} - \Delta p_t$

Step 13: Check If$\lceil \Delta p_{err} \rceil \prec 0$, then set$C_{l.p} = C_{o.p}$and go to step 4

Else if $\lceil \Delta p_{err} \rceil \succ 0$, then set $C_{h.p} = C_{o.p}$and go to step 4

Step 14:CheckTurbine exhaust temperature

If$\lceil T4 - T4r \rceil \approx 0$, then it is correct, go to

step 15:Else If $\lceil T4 - T4r \rceil \prec 0$ set L_{min} = *load* and go to step3

Else setL_{max} = *load* and go to step3

Step15: End processing with Matching complete.

The above algorithm describes how we can get the correct matching point thatsatisfies the set of defined constrains with respect to the selected rational speed and modified the component map according to the corrected factors. Fig. 7 shows a flowchart which simplifies the algorithm to obtain the correct matching point.

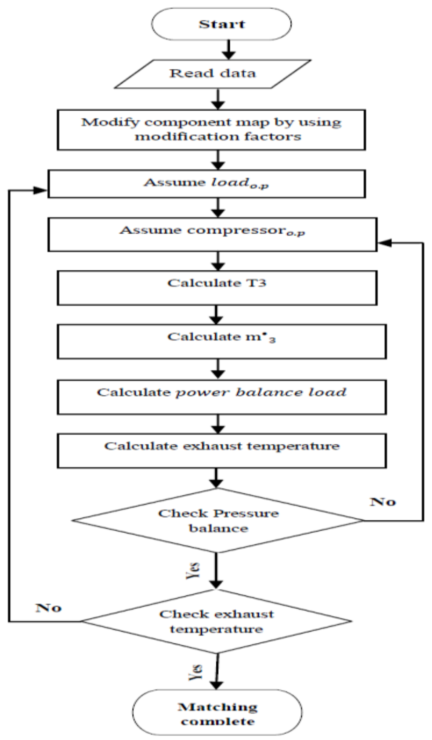

Fig. 7 Correct matching point flow chart

Experimental results and evaluation metrics

To examine the accuracy and efficiency of the proposed model and validate the system analysis, a range of experiments were conducted with settings vary over the number of faults that was presented in Table 1.The process of faults selection was carried out based on the experience and knowledge possessed by expert engineers, these faults caused an economic loss for the plant owner when they occur. Much efforts have been put into consideration in the development techniques to measure and diagnose such faults successfully in order to generate a warning as early as possible through the experiments. These experiments were implemented by Matlab running on Intel(R) Core i3 CPU- 2.53 GHz with 4GB RAM for achieving the set of effective results.

In order to prove the accuracyACC of the proposed mathematical model, we have compared the results with real data according to main measurementssuch as compressor discharge temperature, compressor pressure ratio, inlet turbine temperature, fuel mass flow rate, and engine load of single spool 9EA gas turbine engine during the varying temperatures from 288 to 300Kelvin as shown in equation 1.

$$ACC = (SimRes/RealRes) * 100\% \qquad (1)$$

Where $SimRes$ is the simulated results obtained from the proposed mathematical model and $RealRes$ is the real results obtained from the real engine. The accuracy can measure how close the simulated results is to the actual real results.

Fig.8 shows the accuracy of the proposed model with respect to the compressor discharge temperature. From the figure, we have proven that, the simulated results of the proposed model ranged from 98% to 99% closest to the results of real engine.

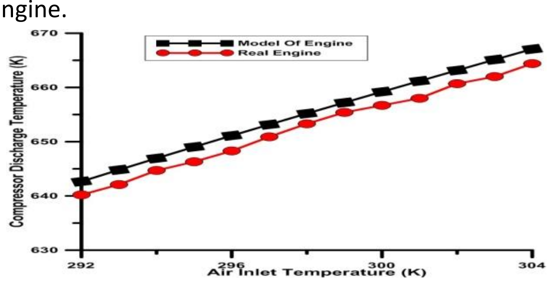

Fig. 8ACC with respect tocompressor discharge temperature.

Fig.9 shows the accuracy of proposed model with respect to the real engine according to the compressor pressure ratio. The results of the proposed model ranged from 98%to 100% (i.e., in some cases) closed to the real model.

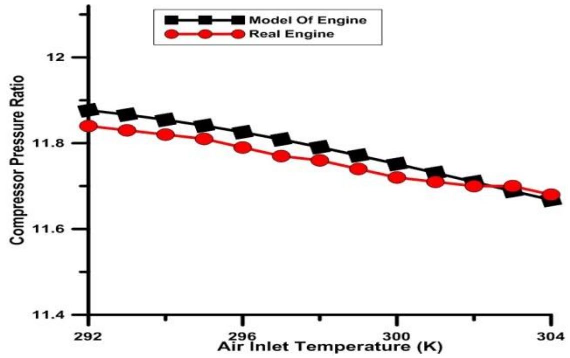

Fig. 9 ACC with respect toCompressor Pressure Ratio.

Fig.10 shows the accuracy of proposed model with respect to the real engine according to the turbine inlet temperature .The results of the proposed model seem to be very close to the real model that was ranged from 99% to 100% in some cases.

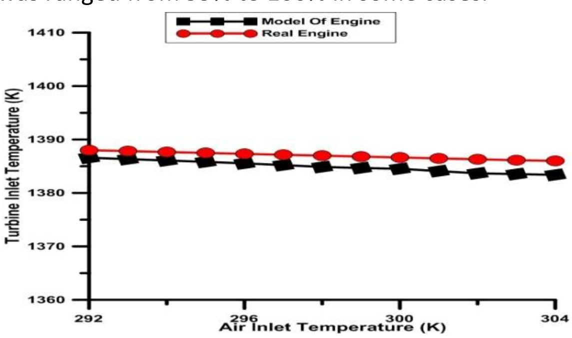

Fig. 10 ACC with respect to Turbine Inlet Temperature.

Fig.11 shows the accuracy of proposed model with respect to the real engine according to the fuel flow rate in which the results ranged from 99%to 100% with increasing of air inlet temperature.

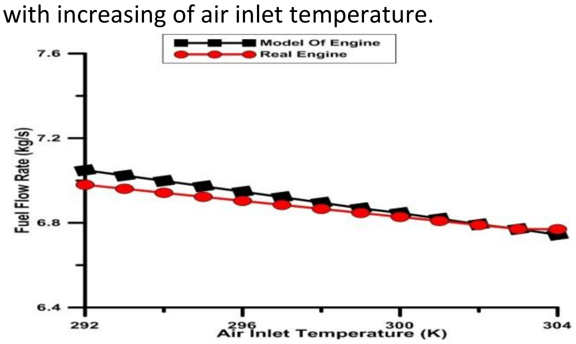

Fig.11ACC with respect to Fuel Flow Rate.

Fig .12 shows the accuracy of proposed model with respect to the real engine according to the engine output load. The results of the proposed model ranged from 99.2% to 99.6% closed to the real model.

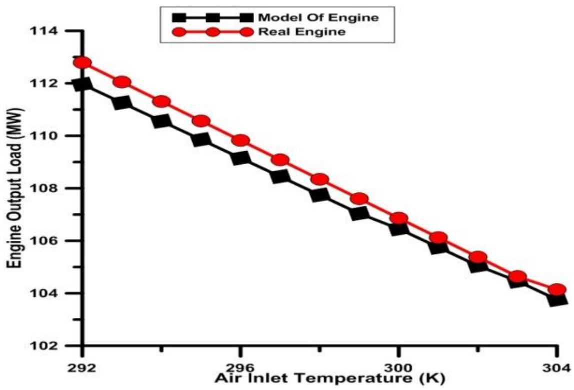

Fig. 12ACC with respect to Engine Output Load.

According to the Air Filter Differential Pressure, fig.13 shows that, the results of proposed model ranged from 95% to 97% closed to the real engine.

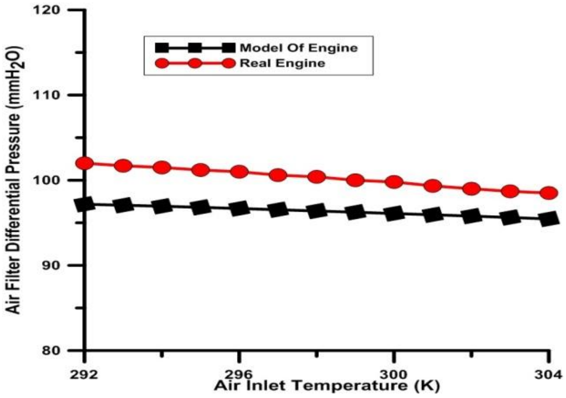

Fig.13ACC with respect to Air Filter Differential Pressure.

The above results have proven that, the accuracy of the proposed mathematical engine model and how it close to the reality and can be relied upon in the engine analysis process according to some faults.

In order to prove the efficiency of the proposed algorithm, the faults were simulated and analyzed in full load (i.e., full speed) conditions of temperatures degree from 288 to 300Kelvin with different fault level (FL%) (i.e., as shown in Table 1). It is well known from the previous study that, the effect of the ambient pressure (*p1*) is linearly and the effect of the relative humidity of the air is rather small[28].Since, the turbine inlet temperature had been estimated to be almost same for all full load conditions in the engine test (i.e., it was kept constant during the simulation). The simulation generated 5760 fault data points and 4032 of them unrepeated fault data points. Seven simulation cases of them without any fault and the rest of simulation cases with faults and their combinations at different levels are shown in Table 2. In which, the degradation percentage of single fault ranged from 0.35~0.5 while the degradation percentage of double faults occurs together ranged from 0.69~1.56.

Table 2 Simulated faults and their combinations.

Fault case	Single fault	Double faults	Triple faults	Quadruple faults	All together
Number of cases	(5)	(10)	(10)	(5)	(1)
Number of occurrences	91	469	1197	1512	756
Degradation range (%)	0.35-0.5	0.69-1.56	2.08-4.68	6.25-9.4	18.75

We can measure the efficiency of the proposed algorithm with respect to the degradation percentage($D.G$) of faults according to compressor or turbine temperature.From equation (11), the $D.G$ can be computed according to the following formula

$$D.G\ (\%) = C.F_{min} - C.F * \left[\frac{100}{C.F_{min} - C.F_{max}}\right] \quad (19)$$

Where $C.F$ is the corrected factor, $C.F_{min}$ *=1* for all fault cases except for *F3*, it equals *1.03*and $C.F_{max} = 0.94$ for all cases exceptforF2, it equals0.96 .

Fig.14 shows how the degradation performance of the engine components affects on the compressor discharge temperature. The increase in the degradation performance of($C.E$)leads to increase in the compressor discharge temperature. The degradation performance of (ALL)has a great effect on the increase of compressor discharge temperature, while the increase of the degradation performance of ($M.R$) leads to the decrease of compressor discharge temperature, From the figure, the degradation performance of ($Com.E$), ($filt.block$) and ($T.E$) affect slightly on compressor discharge temperature.

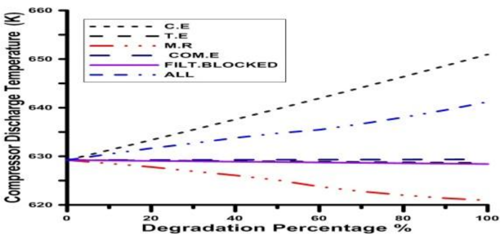

Fig. 14DG with respect to compressor discharge temperature.

Fig.15 shows how the degradation performance of the engine components affects on the compressor pressure ratio. Increase the performance degradation of (ALL) leads to decrease the compressor pressure ratio.Also, increase the performance degradation of ($M.R$) has noticeable impact on decrease the compressor pressure ratio. From the results, it is noticed that, ($C.E$), ($Com.E$) and ($T.E$) seem stable, but after a further deterioration of their performance 30 % showstheir influence on the compressor pressure ratio. Also, increase the performance degradation of *(* $T.E$*),* leads to decrease the compressor pressure ratio and increase the performance degradation of ($Com.E$)and ($C.E$) leads to increase the compressor pressure ratio while, the degradation performance of ($filt.block$) seems constantly unchanged.

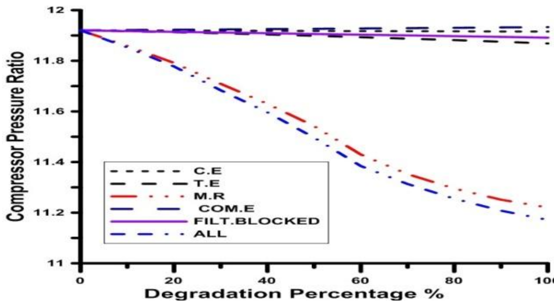

Fig.15DG with respect to compressor pressure ratio.

Fig.16 shows how the degradation performance of the engine components affects on the inlet turbine temperature. In which, increase the degradation performance of (ALL) leads to decrease of compressor discharge temperature followed by the degradation performance of($T.E$) and ($M.R$)leads to decrease of inlet turbine temperature ($C.E$), ($Com.E$),and ($filt.block$) seem stable, but after a further deterioration of their performance 40 % showstheir influence on the inlet turbine temperature. Increase the performance degradation of ($filt.block$), leads to decrease the inlet turbine temperature and increase the performance degradation of ($Com.E$) leads to increase the inlet turbine temperature while, the degradation performance of ($C.E$), seems constantly unchanged.

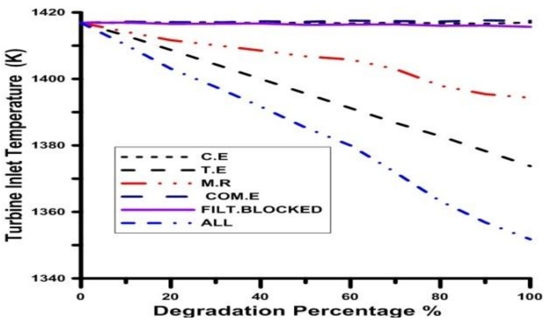

Fig. 16DG with respect to turbine inlet temperature.

Fig.17 shows how the degradation performance of the engine components affects on the fuel mass fuel rate. In which, increase the degradation performance of ($COM.E$)leads to increase of fuel mass flow rate while, the degradation performance of ($filt.block$) constant (i.e., it does not affect on fuel mass flow rate). From the figure, increase of the degradation performance of(ALL) and ($M.R$) lead to decrease of fuel mass flow rate. This effect shown clearly on fuel mass flow rate after60% of increasing deterioration in their performance followed by the degradation performance of($T.E$) and ($C.E$) also has an impact on increase of fuel mass flow rate.

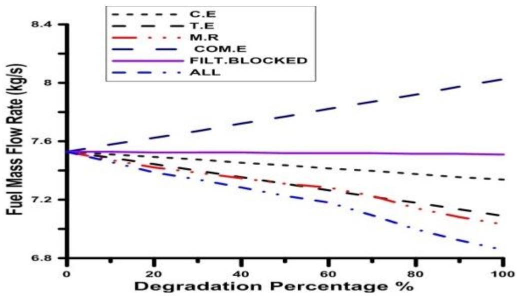

Fig. 17DG with respect to fuel mass flow rate.

Fig. 18 shows how the degradation performance of the engine components affects on the engine loadin which, thedeteriorationin the performance ofeachfaultindividuallysuchas ($C.E, T.E$and$M.R$) has an impact onthedecrease of engine load. While, the degradation performance of (ALL) significantly affect on the decrease of engine load. The impact of the degradation performance of ($COM.E$and$filt.block$) on engine load slightlyunchangeable.

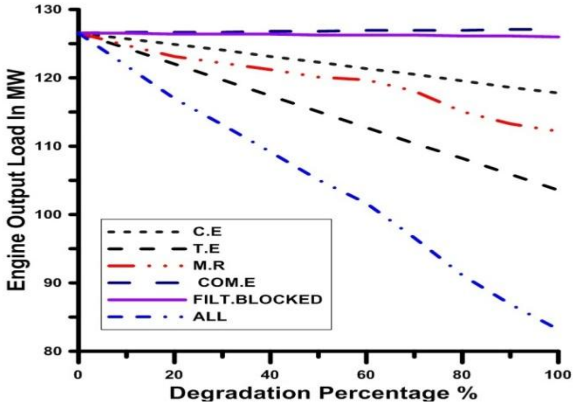

Fig. 18DG with respect to engine load.

The experimental results have been done and verified the thermodynamic model against the real engine measurements data. The results were accurate enough for analyzing and measuring the performance of gas turbine with respect to different faults through proposed matching algorithm. The simulated results show how the degradation performance of the engine components (i.e., compressor efficiency, air mass flow rate, combustion efficiency, turbine efficiency and filter blocked) significantly affects on the compressor discharge temperature, compressor pressure ratio, inlet turbine temperature, fuel mass flow rate, and engine load.

CONCLUSION

This paper focuses mainly on the construction of thermodynamic model of the gas turbine engine. The model is developed to calculate the engine design performance for a single spool industrial gas turbine engine. In which, the difficulties due to the lack of knowledge about stage-by-stage performance are overcome by constructing an artificial machine maps through appropriate scaling techniques applied to generalized maps that taken from the literature and validating them with test measurement data from real plants,A comparison between simulated results and actual values satisfactory approximation was obtained for all the represented variables.. The simulated results show how the degradation performance of the engine components (i.e., compressor efficiency, air mass flow rate, combustion efficiency, turbine efficiency and filter blocked)affects on the compressor discharge temperature, compressor pressure ratio, inlet turbine temperature, fuel mass flow rate, and engine load. The simulated results show that, increasing the degradation performance of combined faults (ALL) leads to decrease each of engine load, the compressor pressure ratio, turbine inlet temperature and fuel mass flow rate. while increase the performance degradation of combustion efficiency leads to increase both of the compressor pressure ratio and fuel mass flow rate .The degradation performance of compressor efficiency leads to increase of compressor discharge temperature while the increase of the degradation performance of air mass flow rate leads to the decrease each of compressor discharge temperature, fuel mass flow rate and compressor pressure ratio. Therefore, the constructed gas turbine model can be used for performance calculation and as a base for further investigations when a diagnosis and supervision system is constructed.

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