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Improvement of Gas Turbine Performance Test in Combine Cycle

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Abstract**—**One of the important applications of gas turbines is their utilization for heat recovery steam generator in combine-cycle technology. Exhaust flow and energy are two key parameters for determining heat recovery steam generator performance which are mainly determined by the main gas turbine components performance data. For this reason a method was developed for determining the exhaust energy in the new edition of ASME PTC22. The result of this investigation shows that the method of standard has considerable error. Therefore in this paper a new method is presented for modifying of the performance calculation. The modified method is based on exhaust gas constituent analysis and combustion calculations. The case study presented here by two kind of General Electric gas turbine design data for validation of methodologies. The result shows that the modified method is more precise than the ASME PTC22 method. The exhaust flow calculation deviation from design data is 1.5-2 % by ASME PTC22 method so that the deviation regarding with modified method is 0.3-0.5%. Based on precision of analyzer instruments, the method can be suitable alternative for gas turbine standard performance test. In advance two methods are proposed based on known and unknown fuel in modified method procedure. The result of this paper shows that the difference between the two methods is below than %0.02. In according to reasonable result of the second procedure (unknown fuel composition), the method can be applied to performance evaluation of gas turbine, so that the measuring cost and data gathering should be reduced.

Keywords**—**Gas turbine, Performance test code, Combined cycle.

I. Introduction

GAS turbines have had a great role in electricity industry during the past four decades. Because of low primary investment cost, gas turbines are used alternatively in order to supply the peak load of power transmission line, and due to short time of startup they have a considerable role in emergency services. Moreover, with regards to the development of natural gas pipelines they are used for driving compressors. One of other ever increasing applications of gas turbines is their use in combined cycle which leads to a high efficiency and power output.

The recent improvement in performance of gas turbines lies in the increase of efficiency of consisting gas turbine components including compressor, combustion chamber, and expander. Some researchers have done studies on evaluation of performance of gas turbines, which can be classified into two major categories. The first group includes studies which have investigated the modeling of parts of the gas turbine cycle, and have tried to troubleshoot gas turbines using component maps and dimensionless parameters of the system [1, 2 and 3], and the second group have investigated the parameters influencing off design performance [4, 5 and 6].

In troubleshooting of gas turbine it is necessary to perform a detailed investigation of performance of each of the parts of the gas turbine cycle. The common point in all cycle parts simulation techniques is the use of component maps. Since most of these kinds of maps are owned by manufacturers and it is hard to access them, other methods are also suggested including similarity consideration and the method using general component maps for compressor and turbine [7].

Besides performance test standards, studies have also been done in order to improve the methods for determination of output or general performance of gas turbines. Yonghong has presented a novel method based on mathematical modeling of steady state performance of gas turbines [8]. In another study, Riegler has proposed some correlations for calculation of heat transfer rate in gas turbine performance calculations [9]. In the paper, heat loss from the gas turbine package surface in transient and steady state has been modeled. In another study which had been done by Zhu et al., a simplified model has been presented for estimation of gas turbine performance in combined cycle [10]. They have been able to identify six key input parameters which are critical in determining the thermal efficiency.

The calculations related to field performance of gas turbines have been increasing recently. These kinds of calculations have been used in order to make sure about the efficiency, output power and operational fuel consumption of gas turbines in economical estimations and guarantee conditions of manufacturer. The above-mentioned calculations are founded on the method which is presented by performance test standards.

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In the present paper, attempts have been made to evaluate and improve the method which has been presented in ASME PTC 22 [11] standard for estimation of energy, flow rate, and temperature of exhaust gases from gas turbines. Considering the increase in energy cost and also environmental considerations, the use of combined cycles have increased, one of the cases where gas turbines have had many applications have been their use as coupled with heat recovery steam generator. In heat recovery steam generator performance evaluation, one of the key input parameters is the flue gas energy(of the gas turbine. Therefore, in the new version of PTC 22 standard a method has been proposed for its estimation, and it is explained in further detail below.

II. The Method for Determining Efficiency-Heat and Mass Balance in Briton Cycle

The procedure for ASME performance test code is one of the most comprehensive performance tests. By performing such tests, power plants operators will be able to acquire more precise information about the current performance of operating units and evaluate the performance of units in different operating conditions, and perform necessary adjustments on equipments which have considerable influence in fuel consumption. Moreover, they can estimate the time required for repairing the faulty equipments by this method. One of these tests is ASME PTC 22 which considers the determination of efficiency of gas turbines with gas or liquid fuel. This test also presents a mathematical method for correction of efficiency, output power, and output energy form the cycle in order to be calibrated with reference conditions. This test can also be used in gas turbines used in combined cycle or other heat-recycling systems.

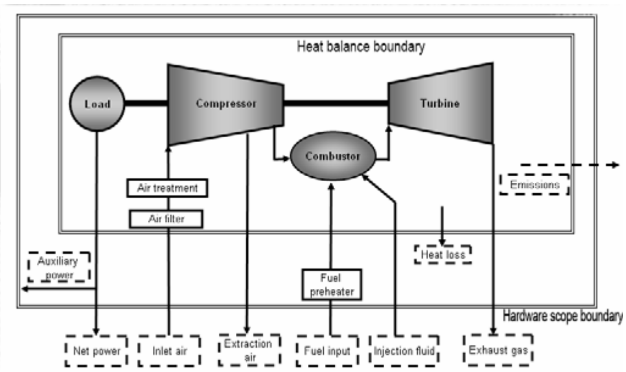

Fig. 1 Control volume considered for performance test of gas turbine based on ASME PTC 22 [11].

The first version of ASME PTC 22 standard was published in 1953. At that time the highest application of gas turbines was in production of peak load and driving compressors, therefore that standard was allocated to output power and gas turbine efficiency determination. When time passed and technology developed the improvement of efficiency and increase in output power, gas turbines became of use for production of base load in combined cycles too. Therefore, in this case the flow rate of flue gas and exhaust temperature are discussed as necessary parameters in investigation of heat recovery steam generator and output of the cycle. Therefore, one of the aims of the new version of ASME PTC 22 standard is the estimation of energy, temperature, and flow rate of flue gas of gas turbines.

The method used in performance tests is based on energy and mass balance using thermodynamic principles. For this purpose, a control volume has been assumed as figure 1, in which measurement points are specified according to the required measurement. In table I the required measurement of each of the flows shown in figure 1 are indicated.

TABLE I
Requirements for Estimation of Thermal Efficiency and Exhaust Flow Rate

1-Inlet air	Pressure, Temperature, Relative humidity
2-Fuel input	Pressure, Temperature, Fuel composition, Flow rate
3-Injection fluid	Pressure, Temperature, Flow rate
4-Flue gas	Temperature
5-Power	Gross power, Power factor
6-Extraction air	Temperature, Flow rate
7-Heat loss	Temperature, Flow rate

Heat losses in the gas turbine include all streams which are considered for generator cooling, lubrication, cooling of gas turbine casing, rotor cooling, and …, which intersect with the boundaries of control cycle. It has to be mentioned that, the heat losses are not taken into consideration when the purpose of the test is just the determination of thermal efficiency.

A. Procedure of performing the test according to ASME PTC 22 standard

Since in this paper the method for estimation of energy and gas turbine exhaust flow rate is dealt with, other parameters discussed in performance determination test like preparations of the test, measurement precision, uncertainty calculations and … are avoided.

The governing equations include energy and mass balance, which are:

$$Q_{air} + Q_{fuel} + Q_{inj} = Q_{ext} + Q_{elect} + Q_{loss} + Q_{exh} \text{ (1)} \qquad (1)$$

$$m_{air} + m_{fuel} + m_{inj} = m_{ext} + m_{exh} \qquad (2)$$

Each one of the terms of equations 1 and 2, excluding the exhaust flow rate and input air can be determined by direct measurement, or an assumed value be considered for them. In this case, there are two equations and two unknowns. The determination of these unknowns is not easily possible due to the dependence of exhaust energy or its enthalpy to air to fuel ratio.

Two methods have been proposed for solution, in the first method the air flow rate is found out using iteration. For this purpose, a assumed value is allocated to the air flow rate, and the input and output energy of the gas turbine is estimated using equation (1), and then air and exhaust flow rate is corrected. These calculations are repeated to the point that two sides of the energy equation are equal.

In the second method, the iteration process is omitted, but this method required the separation of combustion air from input air and exhaust flow. In this method, the stoichiometric combustion air flow rate and the excess air which does not participate in combustion process are considered separately, and all equations can be solved for it without using the iteration method. In the PTC, the second method has been recommended. In this method the following equations have been added to equations (1) and (2) in order to avoid iterations [11].

$$Q_{air} = Q_{air,excess(in)} + Q_{air,comb} \quad (3)$$

$$Q_{exh} = Q_{combprod} + Q_{air,excess(in)} \quad (4)$$

$$m_{combprod} = m_{air,comb} + m_{fuel} + m_{inj} \quad (5)$$

$$m_{exh} = m_{combprod} + m_{air,excess} \quad (6)$$

In other words, in order to determine the flue gas components and finally determining their energy or enthalpy, a set of stoichiometric combustion products enthalpy and enthalpy of excess air have been considered. The amount of stoichiometric air required can be determined using the type and flow rate of the input fuel, and as a result the only unknown will be excess air which can be determined from equation (7). As it can be observed, the above-mentioned method requires the exact determination of component of input fuel, so that the amount of stoichiometric air and related calculations can be performed.

$$m_{air,excess}(h_{air,inlet} - h_{air,exh}) = m_{ext}h_{ext} + Q_{elect} + Q_{loss} - m_{fuel}LHV + m_{combprod}h_{combprod} - m_{inj}h_{inj} \quad (7)$$

In equations (3)-(7) Q is heat transfer, *m* is mass flow rate, *h* is enthalpy, *LHV* is low heating value of fuel and the subscriptions of *excess*, *comb.*, *comprod.*, *exh.*, *ext.*, *elect.*, *loss* and *inj.* are related to excess air, combustor, combustion product, turbine exhaust, extraction air, electric, heat loss and injection fluid respectively.

B. The modified method

According to the present study, the method proposed in ASME PTC 22 standard for estimation of exhaust flow rate has some errors which can be improved. The foundation of this improvement is based on the measurement of flue gas components. For this purpose, it is required to use a flue gas analyzer device at the gas turbine exhaust, so that the dry mole fraction of flue gas components be determined. The sampling method and method of smoke measurement have been explained comprehensively in other standards of performance determination like ASME PTC 4. Therefore, they will not be dealt with here.

In order to estimate the flue gas enthalpy, all exhaust components are needed to be specified, but the analysis which is performed just provides the dry analysis in which the percent of nitrogen and argon compounds and water is not specified separately. The percent of these compounds can influence the estimation of enthalpy to a great extent. In order to surmount this problem, two solutions have been proposed.

The first method: The conversion of dry mole fraction to wet mole fraction components

In this method, amount of either components of fuel is known. By balancing the combustion the number of moles of each chemical component of combustion products can be determined, and as a result convert the dry volume percent to wet volume percent. The calculation procedure has been discussed in the appendix A.

The second method:

In this method, it has been assumed that the input fuel lacks nitrogen and oxygen compounds. However, considering that the combustion air itself contains nitrogen and oxygen, the nitrogen and oxygen in the fuel can be considered inside air contents. According to the above-mentioned assumption and the dry analysis performed, all moles of combustion products can be determined. With regards to the calculations, for different gas fuels and even liquid fuels, this method has an acceptable precision for estimation of flue gas enthalpy. The calculation procedure has been discussed in the appendix B.

III. Results and Discussion

A. Case study

TABLE II
DESIGN DATA OF TWO GAS TURBINE TYPES

Turbine type	GE7241FA	GE7251FB
Output power (kW)	171103	183355
Air pressure (bar)	1.01	1.01
Air temperature (C)	15	15
Relative humidity (%)	60	60
Fuel mass flow rate (kg/s)	10.17	10.699
Exhaust mass flow rate (kg/s)	453.91	451.07
Fuel type	Natural gas	Natural gas
Flue gas compositions	0.82 (Ar+N2) 0.13 (O2) 0.04 (CO2)	0.82 (Ar+N2) 0.13 (O2) 0.04 (CO2)
Flue gas temperature (C)	603	629.4

In order to determine the precision of the proposed method, the design data of two gas turbine types have been used according to table II. If it is assumed that the exhaust flow rate of design state is unknown, by using other data it can be estimated by PTC22 method and the present modified method, and then the degree of precision of results can be presented.

The results of gas turbine exhaust flow calculation have been presented in table 3. It can be observed that the difference between results of the method presented in ASME PTC 22 and the design data is about 1.5 to 2 percent, but with the present modified method this difference is much lower and is about 0.25 to 0.35 percent that is because of estimation of flue gas enthalpy. In the present method, the enthalpy of the flue gas is found by measurement of flue gas components and balancing of the combustion, and is more precise in comparison to the standard method of ASME PTC 22 which calculates the enthalpy of flue gas assuming that the combustion is complete and no excess air participates in the combustion. As a result, the degree of error is lower than the method presented in ASME PTC 22 method.

Another advantage of the present method in comparison to ASME PTC 22 is the way of considering incomplete combustion. In the present method effect of presence of un-burned carbon and carbon monoxide gas in the products of the combustion in a way show the incompleteness of the combustion has been considered by considering the combustion efficiency in energy balance equations. The investigations about the present case indicate that the 0.05 percent deviation from the complete combustion efficiency ($\eta = \boldsymbol{100}\%$) can cause an error of about 0.1 percent in estimation of exhaust mass flow rate.

B. The comparison of the modified method in two cases: fuel with known components, and unknown fuel

In this section, the precision of the modified method has been investigated by the assumption that the components of the input fuel are unknown. In this method, it has been assumed that the fuel lacks oxygen and nitrogen compounds. For this purpose, a fuel has been considered that contains a percent of oxygen and nitrogen. The information of the elements forming the input fuel has been summarized in table IV. This information is related to natural gas, in which the weight percent of nitrogen and oxygen is 5.71 and 0.82, respectively.

In order to compare the two methods, once again the calculations of performance determination for gas turbine was performed based on design data presented in table II for turbine GE7241FA, disregarding the components of input fuel.

The results of the calculations have been presented in table V. As it can be observed, the results are of an acceptable precision.

IV. Conclusion

In this paper, a method was presented for improvement of performance test code of gas turbines based on information which can be obtained operationally. The calculations performed for two gas turbine types manufactured by GE Company indicated that the precision of calculation method ASME PTC 22 regarding the flow rate of flue gas can be improved by more than one percent. Since the exhaust flow rate is usually used for heat recovery steam generators, this degree of improvement in calculation precision can have a considerable role in estimation of efficiency of heat recovery steam generators. Also, in this paper a method was presented by which the calculations of performance estimation of gas turbine be performed without measuring the input fuel components. A calculation performed for a fuel which contained a percent of oxygen and nitrogen indicated the acceptable precision of this method, in a way that the error of calculations was found out to be lower than 0.02 percent. Due to the fact that the results presented in the present study are of high precision, and it is possible to perform performance test with the proposed method with data which can be acquired in operational state, it is suggested that the method presented by ASME PTC 22 standard be replaced with the modified method.

TABLE IV
Natural gas compositions analysis

Weight percent (%)	Fuel composition
C	70.69
H	22.71
O	0.8208
N	5.701
S	0.0723
Ar	0
Water vapor	0.0

TABLE V
The results of performance determination of GE7241FA turbine with two modified methods

	Known fuel	Unknown fuel	Percent of error (%)
Exhaust flow	452.31	452.23	0.018
Exhaust energy	1038539011	1038535227	0.000

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