A NOVEL METHOD FOR PREDICTION OF GAS TURBINE POWER PRODUCTION
Degree-Day Method

by

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Gas turbines are widely used in the energy production. The quantity of the operating machines requires a special attention for prediction of power production in the energy marketing sector. Thus, the aim of this paper is to support the sector by making the prediction of power production more computable. By using the data from an operating power plant, correlation and regression analysis are performed and linear equation obtained for calculating useful power production vs atmospheric air temperature and a novel method, the gas turbine degree day method, was developed. The method has been addressed for calculating the isolation related issues for buildings so far. But in this paper, it is utilized to predict the theoretical maximum power production of the gas turbines in various climates for the first time.
The results indicated that the difference of annual energy production capacity between the best and the last province options was calculated to be 7500 MWh approximately.

Key words: *gas turbine, degree day, prediction of energy production, ambient temperature, energy prediction*

Introduction

Gas turbines are highly preferred and used devices for the power generation systems (esp. in combined cycles) because of their advantages *e. g.* high efficiency, flexibility, short start-up period, *etc*. [1-3]. Including a similar machine that is jet air craft engine, today there are large amount of gas turbines operating all over the world [4]. Therefore, the size of the market attracts the attention of investors and so do the researchers. Some of the researchers are focus on the mechanics of gas turbines [5] some are interested in the thermodynamics [6] and even in some studies gas turbines are examined because of their vital effect on another power cycle [7].

The size of the market forces researchers to investigate the existing gas turbines to operate more efficiently. Determination of the amount of production, energy consumption and economic merits are very important for these machines during the investment decision [8] and operation [9]. On the other hand, operating a power plant in a most effective way can increase the profit of this huge market. Basha *et al*. investigated the fogging system to boost an existing GT cycle [10], Escudero *et al*. analyzed alternative fuels for firing a gas turbine [11], Erans studied on a process modelling of a combined cycle [12] and optimization studies are performed to investigate the best operating options using *e. g.* MOPSO algorithm [13] or genetic algorithm [14].

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Generally in optimization studies such as [15-17] the environmental conditions, *e. g.*, inlet air temperature are assumed to be constant but the effect of variation of these conditions on the performance may be more than 25% which is not a negligible amount [18]. There are satisfactory amount of publications in the literature which relates the output power of the gas turbine and ambient temperature [19, 20]. Tufekci examined and compared machine learning regression methods to develop a predictive model for predicting the hourly full load power generation of a combined cycle power plant [21]. De Sa and Zubaidy proposed an empirical relationship between the generated power of a gas turbine and ambient conditions of the site [22]. Rashid *et al*. presented a particle swarm optimization trained feed-forward neural network approach to predict power plant output [23]. Alsairafi examined the effect of ambient conditions on the thermodynamic performance of a hybrid combined-nuclear cycle power plant [24]. Al-Fahed investigated the effect of increased inlet air temperature and relative humidity on the performance of a gas turbine cogeneration system [25]. Singh and Kumar investigated the effect of the ambient temperature on the performance of a combined cycle power plant [26, 27]. Bihari *et al*. have introduced a correlation for various types of power plants. The correlation has 2 correction factors and one of them is the ambient parameters such as temperature, season and geographic location of the power plant [28]. Some of these studies applied useful methods to predict the power production of a certain location but they do not offer a comparison between the production potentials for different locations. This paper represents a quantification study to define the magnitude of the relationship between the ambient temperature and power generation for various locations with different climates.

Since these machines are volumetric flow devices the power generation of a gas turbine is highly dependent to the ambient temperature [29]. This means, the power production will vary according to the climate of the location of the power plant and that makes the production unpredictable. The positive effect of the cold climates on the gas turbines is well known but it is uncertain that how much power will be produced in various climates.

Thus, this study aims at developing a novel method for gas turbines to make the prediction of power production more than a forecast, to make it accountable. The gas turbine degree day (GTDD) method was adapted and developed from the known degree-day method that has been used for building related studies. But for the first time the method is utilized for gas turbines by using some additional analysis such as correlation and regression analysis. The contribution of this paper to the literature is the addition of this novel method.

The power generation data for one year of an F701 type Mitsubishi Heavy Industries (MHI) gas turbine was collected from Ovaakca power plant. The GTDD method was introduced and utilized to obtain the theoretical maximum production potential (TMPP) of the gas turbine after correlation and regression analysis. Finally, the TMPP for 23 provinces in various climates were calculated and discussed.

Material and method

In this study, GTDD method was employed to determine the TMPP of gas turbines in various climates. With this method, just like forecasting the insulation thickness of buildings [30, 31], gas turbine production can be forecasted if the atmospheric behaviour of the power plant location and gas turbine characteristics are known. In this paper, 701F type gas turbine (GT) which is produced by MHI and located in Ovaakca power plant in Bursa Turkey was investigated. The specifications of the 701F gas turbine are given in tab. 1.

Table 1. Specifications of the gas turbine

Specification	Variable	Specification	Variable
Manufacturer	MHI / Japan	Critic Rev.	1. Critic 930 2. Critic 2550
Type	Axial flow – 701F	Start-up time	1200 sec
Gross output power	239 MW	Combustion chamber type/num.	Multi cell / 20
NO_x emission	50 mg/m^3	Ignition	Spark
Number of blade stage	4	Compressor type	Axial flow
Inlet temperature	1350 °C (ISO)	Stage number	17
Exhaust temperature	558 °C	Compression ratio	16
Revolution per minute	3000 rev/min	Air-flow (ISO)	580 kg/s (%100 load, 15 °C)

In fig. 1, T_r, T_i, W_r, and W_i represents the reference temperature, the ambient temperature at i^{th} hour, the power production at the reference temperature and the power production at the i^{th} hour respectively. The power production difference (ΔW) between the reference temperature and the i^{th} ambient temperature is:

$$\Delta W = W_r - W_i \tag{1}$$

and the slope of the curve (R_b) is:

$$\tan\theta = R_b = \frac{\Delta W}{\Delta T} = \frac{W_r - W_i}{T_r - T_i} \tag{2}$$

Combining eqs. (1) and (2) power difference becomes:

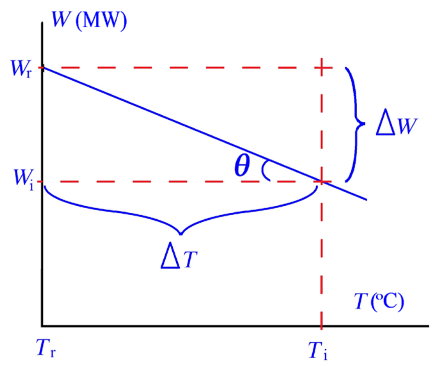

Figure 1. Schematic representation of the variation of energy production of a gas turbine *vs.* ambient temperature

$$\Delta W = R_b \left(T_r - T_i\right) \tag{3}$$

The production changes ΔW amount against the each degree of ambient temperature increase. Now Wi, can be calculate:

$$W_i = W_r - \Delta W = W_r - R_b \left(T_r - T_i\right) \tag{4}$$

Additionally, this equilibrium can be written as the general form of linear regression:

$$Y = a + bX \tag{5}$$

where Y represents the dependent variable (in this paper it is W_i), a is the regression constant equals to (W_r), b is the regression coefficient equals to (R_b) and X is the independent variable equals to ($T_r - T_i$).

A sample of average daily energy production curve of considered gas turbine is represented in fig. 2. Average of last 7 days from a random month that is July in this case is calculated for temperature and for power production. The blue curve represents the hourly recorded power production and red curve represents the atmospheric temperature. The T_{dm} and V_{dm} represent

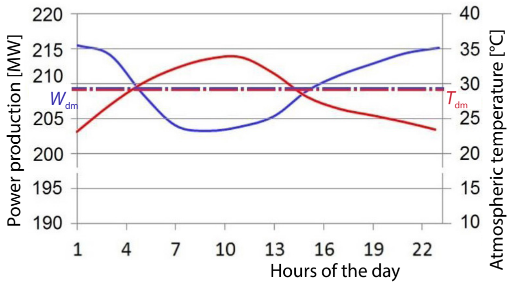

Figure 2. The schematic illustration of hourly production *vs.* ambient temperature during a day

the daily mean temperature and daily mean power production, respectively. The inverse relationship between the slopes of two lines is in an agreement with the inverse correlation. In fig. 2 the area below the blue line is proportional with the daily energy production and decreases until the warmest hour of the day and then increases until coolest hour of the day. Each column represents the maximum energy that the gas turbine can produce based on the atmospheric temperature at i^{th} hour in MWh. Thus, the daily energy production can be integrated from the blue curve or can be calculated easily from the area of the rectangle below the W_{dm} line since a linear correlation exists between the power production and atmospheric temperature. Both methods are suitable for calculating the daily power production but in this study first approach will be employed. The daily energy production of k^{th} day ($W_{d,k}$) can be calculated:

$$W_{d,k} = \Sigma_{i=1}^{24} W_i \tag{6}$$

and substituting with eq. (4):

$$W_{d,k} = \Sigma_{i=1}^{24} \left[W_r - R_b (T_r - T_i) \right] \tag{7}$$

If the daily mean temperature is introduced as in eq. (8), the daily production capacity ($W_{d,k}$) can also be expressed in terms of the area below the daily average temperature as in eq. (9):

$$T_{dm} = \frac{\Sigma_{i=1}^{24} T_i}{24} \tag{8}$$

$$W_{d,k} = 24 W_{dm,k} \tag{9}$$

Summation of the produced energy in 365 days throughout a year gives us the annual theoretical maximum production capacity (W_y) and it can be calculated by using the eq. (10).

$$W_y = \Sigma_{k=1}^{365} W_{d,k} = \Sigma_{k=1}^{365} \Sigma_{i=1}^{24} \left[W_r - R_b \left(T_r - T_i \right) \right]_k \tag{10}$$

In the literature there are plenty of publications which presents the cooling degree day for various purposes [30, 31]. However, in this study, the reference temperature was taken as 40 °C and named as GTDD. In accordance with the references the GTDD can be expressed:

$$\text{GTDD} = \Sigma_{k=1}^{365} \left(T_r - T_{dm} \right)_k \tag{11}$$

Equation (11) accounts for DD of the k^{th} day. Combining eqs. (11) and (8):

$$\text{GTDD} = \Sigma_{k=1}^{365} \left(T_r - \frac{\Sigma_{i=1}^{24} T_i}{24} \right)_k \tag{12}$$

and this statement yields to eq. (13) since T_r is a constant value that should be defined according to the location of the power plant:

$$\mathrm{GTDD} = \frac{\Sigma_1^{365}\Sigma_1^{24}\left(T_r - T_i\right)}{24} \tag{13}$$

Substituting eq. (10) and utilizing GTDD from eq. (13) W_y can be written:

$$W_y = 8760 W_r = GTDD\, R_b \tag{14}$$

With this model the TMPP can be calculated for a specific gas turbine that is operated in various climatic location at full load for 365 days and 24 hours. However, climate conditions and status and operation hours of the gas turbine contain many parameters. But the other parameters that can affect the power production are not included in the scope of this study. These factors can be summarized as:

– the relative humidity,
– the altitude,
– the manufacturer, make and model of the turbines,
– the age and condition of the turbines (how many stops/ starts/ hours/ maintenance time *etc*.),
– the control systems,
– the heat and water balance parameters for the HRSG,
– the configuration and age of the HRSG,
– the configuration and layout of the intake and exhaust systems,
– the chemical composition of the natural gas, and
– the pressure that the gas it is delivered to the site and if compressors are used to adjust the pressure for the turbines.

Results and discussion

In this study, the predicted theoretical maximum annual electrical energy productions for alternative provinces which have different climate conditions than Bursa were calculated via gas turbine degree-day method and the results were compared between the provinces. The appropriate expression for useful work calculations for the selected gas turbine was obtained with correlation and regression analysis. The data used in the analysis were provided from the previous publications [32].

The results of correlation and regression analysis

Figure 3 represents the variation of the useful work (W_i) at full-load *vs*. atmospheric temperature (T_i) of a single gas turbine of Bursa Ovaakca power plant. The figure shows that the useful work is decreasing against the increasing atmospheric temperature. The relationship between these two variables seems to conform to a correlation.

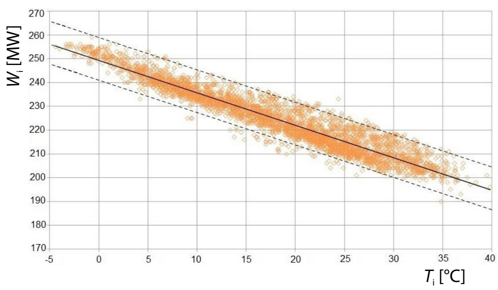

Figure 3. Measured useful work *vs.* atmospheric temperature

In this paper correlation and regression analysis were applied to the gas turbine of Ovaakca power plant. Comprehensive information about the correlation and regression analysis can be found in [33-35]. The correlation coefficient was calculated as $r = -0.968395$ by using the useful work as the dependent variable and the atmospheric temperature as the independent variable. This high rate of r that is so close to -1 is an evidence of the inverse relationship between the useful work and the atmo-

Table 2. Coefficients of the regression equation

a	b	Standard deviation (%)
–1.3638	249.31	13.11

spheric temperature. To calculate the useful work from a single gas turbine, eq. (15) was obtained by linear regression analysis and tab. 2 represents the results of correlation and regression analysis.

$$\dot{W}_i = -1.3638 T_i + 249.31 \tag{15}$$

The useful work at the 0 °C and the useful work at the maximum measured atmospheric temperature (40 °C) were calculated as 249.31 MW and 194.76 MW, respectively. These values are in a good agreement with the measured data. On the other hand, it is determined that every 1°C increase in atmospheric temperature will cause 1.36 MW power loss.

The GTDD of the selected provinces in Turkey

The T_{dm} of the considered 23 provinces (including Bursa) were calculated using the hourly temperature data taken from Provincial Directorate of Meteorology in Yalova between the years 2005-2015. The T_r was taken as 40 °C in the calculations of degree day of each province. Figure 4 represents the degree days of 23 provinces that have various climates and their province codes. The horizontal line in the figure represents the degree day of Bursa. It is observed that Erzurum (code 25) has the highest GTDD that is 12478 and Mersin (code 33) has the lowest GTDD that is 6983. In fact, Erzurum is the coldest and Mersin is one of the hottest provinces of Turkey. Because of this the GTDD of Erzurum is nearly twice as the GTDD of Mersin. Noting that Mersin is near the Mediterranean Sea while the altitude of Erzurum is 1893 m, this paper concerns with the effect of atmospheric temperature on the power production gas turbines and other parameters those effect gas turbine performance are not considered.

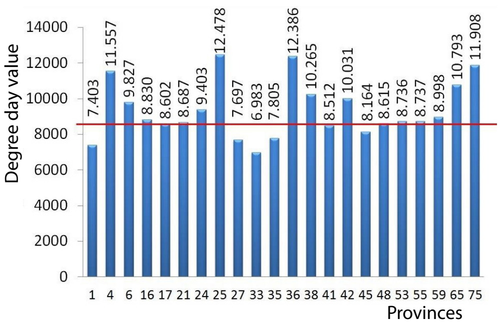

Figure 4. The GTDD of the considered provinces

The GTDD approach for theoretical maximum annual electricity energy production in provinces

The estimated TMPP for each province according to the developed method is given in fig. 5. It is seen that the overview of figs. 5 and 4 are similar. It should be noted that the predicted energy production values in the fig. 5 are the theoretical maximum production potentials. The actual production would change with the annual operating hours of the plant and the other effects. This method is a useful tool to quantify the effects of atmosphere temperature on the electricity energy production. As a result, 10 provinces which have higher degree day values than Bursa that stayed below the horizontal line can be considered as a better alternative. The rest 11 provinces cannot be considered as an alternative since their energy production cannot provide the production in Bursa as observed in fig. 5.

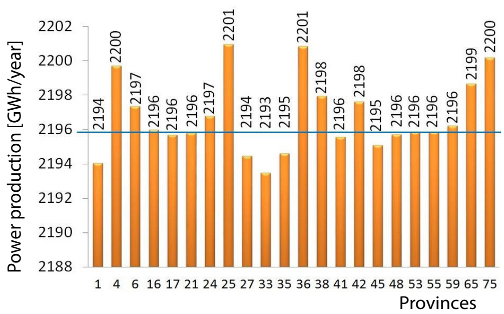

Figure 5. The TMEP of the 23 provinces

Table 3. Potential TMEP in provinces

Code	Province	W_u [MWh per year]	$W_u - W_r$ [MWh per year]	$W_u - W_r$ [%]
25	Erzurum	2,200,973	4,975	0.227
36	Kars	2,200,848	4,850	0.022
75	Ardahan	2,200,196	4,198	0.191
4	Agrı	2,199,717	3,719	0.169
65	Van	2,198,675	2,677	0.122
38	Kayseri	2,197,955	1,957	0.089
42	Konya	2,197,636	1,638	0.075
6	Ankara	2,197,358	1,360	0.006
24	Erzincan	2,196,780	782	0.036
59	Tekirdag	2,196,228	230	0.010
16	Bursa	2,195,998	0	0
55	Samsun	2,195,870	–128	–0.006
53	Rize	2,195,870	–128	–0.006
21	Diyarbakır	2,195,802	–196	–0.009
48	Mugla	2,195,705	–293	–0.013
17	Canakkale	2,195,687	–311	–0.014
41	Kocaeli	2,195,564	–434	–0.020
45	Manisa	2,195,090	–908	–0.041
35	İzmir	2,194,600	–1,398	–0.064
27	Gaziantep	2,194,453	–1,545	–0.070
1	Adana	2,194,052	–1,946	–0.089
33	Mersin	2,193,479	–2,519	–0.115

In tab. 3, the annual energy production value of the considered GT is compared with the potential TMEP of the other provinces. The 10 possible and 11 unsuitable alternative provinces were presented. It is observed the provinces where the climate conditions are warmer than Bursa are not good alternatives and the provinces located in the eastern region of Turkey offers better alternatives according to Bursa because of their climate with lower atmospheric temperature and low GTDD. Finally, the analysis showed that the Erzurum is the most suitable alternative for a gas turbine location according to Bursa (tab. 3). If the power plant was constructed in Erzurum instead of Bursa, the TMPP may be 4975 MWh more in a year that is 0.227% of the annual production. But of course it must be noted that other parameters should be considered in the selection of location of a gas turbine power plant.

Conclusions

In this study, GTDD method was utilized as a novel and diagnostic tool to predict the theoretical maximum power production of a known gas turbine in various locations and climate conditions. This useful tool was addressed to decision makers to help in their decisions about selection of the location of gas turbine power plants.

The production data of 13 months *vs*. ambient temperature of a F701 type MHI gas turbine was processed. A linear equation was obtained as a result of regression and correlation analysis that were applied to demonstrate the relationship between ambient temperature and the power production. The effect of temperature decease on the power production is calculated 1.36 MW/°C. GTDD method was introduced in the calculations of the TMPP. With the results of introduced method, the TMPP of the gas turbine in 23 different provinces were calculated. The maximum TMPP of the gas turbine was calculated to be 2 200 973 MWh annually that is 4975 MWh more than the location where power plant is actually operating. Thus, as a comparison parameter TMPP was introduced and quantitatively calculated.

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