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Dependence between nominal power deterioration and thermal efficiency of gas turbines due to fouling

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Abstract

Deterioration in the performance of gas turbines is a well-known phenomenon occurring during their operation. The most important form is a decrease in the internal efficiency of the compressor and turbine due to fouling, which is the most significant deterioration problem for an operator. This article presents the effect of gas turbine fouling as a drop in airflow, pressure ratio, and compressor efficiency resulting in a reduction in power output and thermal efficiency. This resulted in a decrease in the nominal power of a gas turbine and an increase in the fuel consumption (heat rate). The fouling effects were described using the example of the MT30 marine gas turbine with a nominal power of 36 MW. The estimated profit loss during the operation of the gas turbine was within the range of 1–10% of the total fuel consumption cost. A 2% deterioration in the output of a gas turbine accounted for US$ 10,000–20,000 per year and 1 MW of gas turbine nominal power (according to marine fuel prices in 2019–2020) – this means at least US$ 300,000 annually for an MT30. Due to the low accuracy of fuel consumption measurements, another possibility was provided. The correlation between the gas turbine power deterioration and thermal efficiency was presented, which made it possible to estimate the increase in the specific and total fuel consumption when the nominal power deterioration is known. Two linear approximations were proposed to calculate increases in the annual operating costs for an MT30 due to fouling.

Nomenclature

$c_p = c_{p\mathrm{AIR}}$ – specific heat of air at constant pressure [J/kgK];
GT – gas turbine;
HR – heat rate [kJ/kWh];
IGV – inlet guide vane;
$l_{i\mathrm{GT}}$ – internal specific work of gas turbine [J/kg];
LHV – low heat value of fuel [kJ/kg];
$\dot{m}$ – mass airflow [kg/s];
mt – metric ton as a unit of purchased fuel; mt = 1000 kg;
m_C – coefficient of compression $m_C = (\kappa_C - 1)/\kappa_C$;
m_T – coefficient of expansion in turbine $m_T = (\kappa_T - 1)/\kappa_T$;
NWR – network ratio [–];
κ_C – adiabatic coefficient for air (compressor) [–];
κ_T – adiabatic coefficient for exhaust gases (turbine) [–];
$P_{i\mathrm{GT}}$ – internal power of gas turbine [W];
p_1 – ambient pressure [Pa];
p_{1i} – air filter exit pressure on the inlet to the compressor [Pa];
p_2 – compressor exit pressure, inlet to the combustion chamber [Pa];
p_3 – combustion chamber exit pressure [Pa];

p_4 – outlet duct exit pressure (beyond the turbine) [Pa];
PHR – percentage of heat rate increase [%];
PPR – percentage power reduction [%];
PR – pressure ratio, compression ratio [–];
Δp_1 – pressure drop on air filters [Pa];
Δp_3 – pressure drop in the combustion chamber [Pa];
Δp_4 – pressure drop between the turbine outlet and ambient pressure (overpressure) [Pa];
SFC – specific fuel consumption [kg/kWh];
TIT – temperature inlet to the turbine [K], see: T_3;
T_1 – ambient temperature [K];
T_3 – temperature at point 3, inlet to the turbine [K];
β – molecular change coefficient of the working medium [–];
η_{iC} – isentropic (internal) efficiency of the compressor [–];
η_{iT} – isentropic (internal) efficiency of the turbine [–];
$\eta_{i\mathrm{GT}}$ – thermal efficiency of the gas turbine [–];
US$ – United States Dollar.

Introduction

Fouling is the most significant deterioration problem for a gas turbine (GT) operator. Undesirable roughness due to the accumulation of unwanted material in the aerodynamic foil of GT (compressor and turbine) blades is referred to as fouling. It has a significant impact on the first 3–4 stages of compressors and the 2–3 stages of a high-pressure turbine. The effects of fouling include a decrease in air flow through the compressor, lower compressor exit pressure, and lower isentropic efficiency of the compressor and the turbine (Stalder & Sire, 2001; Syverud et al., 2003). The result is a decrease in the power output and an increase in heat rate (HR). It means a deterioration of the GT performance and an increase in an adverse impact on the environment. It has been estimated that fouling can result in 70–90% of overall performance losses in gas turbines (Liu et al., 2017, Radthee, Dev & Kumar, 2012). Other consequences include a pressure drop on inlet filters, a pressure drop in flow channels, a pressure drop in the combustion chamber, and overpressure in the exhaust duct.

The basic types of fouling include (Soares, 2008; Kurz & Brun, 2012; Liu et al., 2017):

- Particulate matter – dust and sand that have entered through air filters with oily vapors can lead to erosion and fouling;
- Hydrocarbons – increasing the amount of deposit on the blades due to catching particulate matter from burnt fuels;
- Saltwater – when the moisture in the air evaporates, it leaves salt and other dissolved constituents. The process of baking it onto the surface of blades creates hard deposits and causes corrosion and rust. This is a major problem at sea, in coastal industries, and offshore;
- Leaks of internal gas turbine lubricating oil;
- Other causes – atmospheric air contains more contaminants such as chemicals and cleaning additives, which, if not rinsed off properly, can add to the fouling deposits.

The inlet duct and first stage of the compressor often become severely fouled. The remedy for this is cleaning these parts by hand when the gas turbine is stopped.

Washing procedures to remedy fouling

The challenge is to find the best washing procedures for specific needs related to the arrangement and location of gas turbines. Washing is the method specified by the turbine manufacturer, and regular washing is the best method for removing the foulants. Two basic methods of washing are (Stalder & van Oosten, 1994; Tarabrin et al., 1998; Jeffs, 2003; Mund & Pilidis, 2004; Schneider et al., 2010; Rahman, Ibrahim & Abdalla, 2011; Meher-Homji, Bromley & Stalder, 2013):

- Off-line washing – the gas turbine should be in a cold state. After it has been turned at the crankshaft speed, a chemical solution should be injected into the compressor. The chemicals, together with the air that has been drawn in, go through all parts of the gas turbine to the outlet duct. The engine is then shut off. The chemicals are left to soak in for 20–30 minutes, after which the turbine is rinsed with demineralized and deionized water;
- On-line washing – the gas turbine is at its normal operation. Washing is conducted by regular spraying of a cleaning solution into the compressor that is running at full speed. The short time that the cleaning solution has with the fouling layer is the reason for the decreased effectiveness of this method.

The off-line washing method requires the turbine to be taken out of operation and cooled. The procedure takes about one hour. This presents a great disadvantage, but the efficiency is very high, allowing the turbine efficiency and power recovery to reach

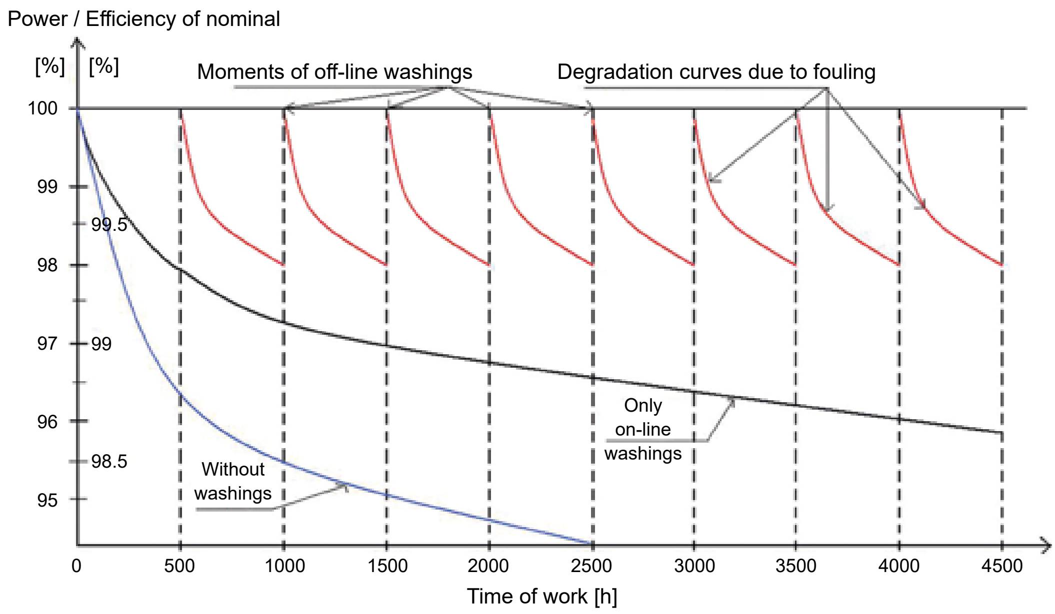


Figure 1. The change of gas turbine power and efficiency due to fouling and its recovery after using washing methods (based on Meher-Homji, Bromley & Stalder, 2013)

nearly their original levels (allows reaching the nominal power).

The on-line washing method improves the availability of a gas turbine by slowing the rate of its performance loss (power and efficiency) and prolongs the time between off-line washes. It is important to use a suitable detergent that improves the cleaning effects while reducing the total amount of liquid required per wash.

It is possible to use both of the washing methods mentioned above. The process of degradation of a gas turbine's performance is illustrated in Figure 1.

The process of degradation of the gas turbine performance depends on many parameters (Jeffs, 2003; Syverud et al., 2003; Bromley, 2012):

- The quality of air filtering (amount and type of contaminants in the air supply);
- Type of fuel used and the engine load (influences the burning process);
- Type of the gas turbine arrangement (simple cycle, steam injection, humidified or wet suction).

As a priority, on-line washing should be performed at predetermined regular intervals. The determination of the timing of off-line washing is more complex depending on:

- Decision of the user (or owner) concerning the acceptable level of power and efficiency degradation;
- Decision on shutting down and cooling the gas turbine is possible only when external conditions allow the gas turbine to be stopped (the timing may be changed slightly).

This means that there can never be one universal washing procedure. The most beneficial regime of washing is usually developed through experience and should be customized for every gas turbine, especially the compressor.

The need to keep the best possible internal efficiency of the compressor and turbine

Keeping the internal efficiency of the compressor and turbine as high as possible is the operator's basic duty. Why is it so important? Looking at an open cycle of a gas turbine (Figure 2 – blue lines), it may be noticed that there are many differences compared to the theoretical Joule-Brayton cycle (red lines).

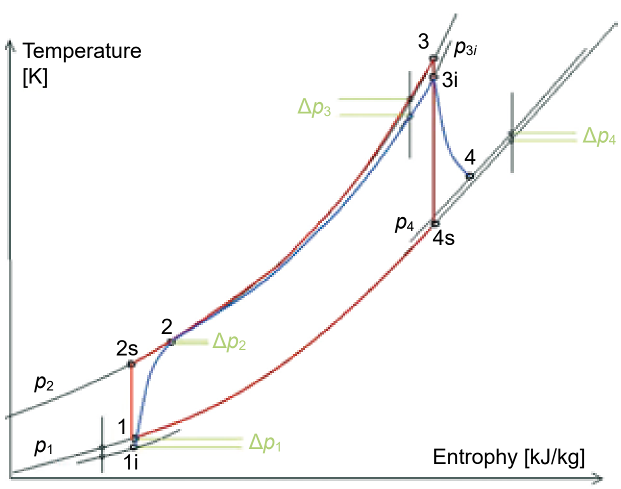


Figure 2. The open cycle of a turbine (blue lines) in comparison with the theoretical J-B cycle (red lines)

Simplifying some dependencies may result in using equation (1) for calculating the efficiency of the gas turbine as (see Figure 2 and the nomenclature):

$$\eta_{i\mathrm{GT}} = \\ = \frac{\frac{T_3}{T_1}\left[1-\left(\frac{p_{3i}}{p_4}\right)^{-m_T}\right]\eta_{iT}\cdot\eta_{CC}-\left[\left(\frac{p_2}{p_{1i}}\right)^{m_C}-1\right]\frac{1}{\eta_{iC}}}{\frac{T_3}{T_1}-1-\left[\left(\frac{p_2}{p_{1i}}\right)^{m_C}-1\right]\frac{1}{\eta_{iC}}} \tag{1}$$

The change from point A to point B due to fouling results in an increased pressure ratio, decreased compressor efficiency, and volumetric airflow (Figure 3). Moving point B closer to the surging line poses a risk of dangerous surges. For marine gas turbines, which work as prime movers, this may result in operation of the gas turbine within the range of open anti-surge valves (Dzida & Frost, 2017). This means working on unstable characteristics with many problems (unstable parameters of the gas turbine, especially the load and rotational speed). This remains important when the gas turbine drives the fixed-pitch propeller and works on the propeller characteristics, which may quickly change due to adverse sea conditions.

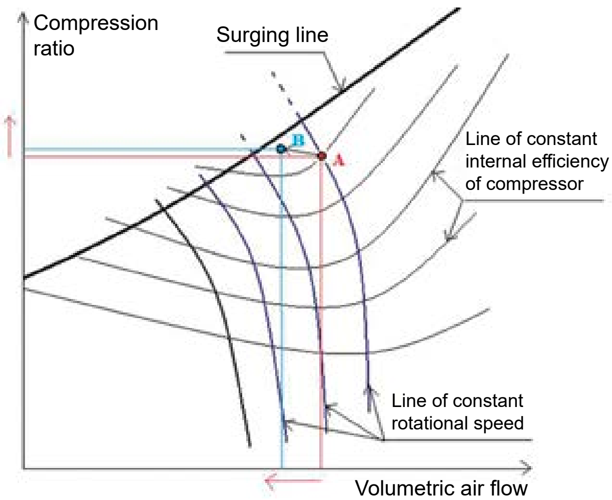


Figure 3. The change of the gas turbine parameters due to fouling

By using the following data (possible for the MT30 marine gas turbine (Edge, 2016; Herdzik & Cwilewicz, 2017)):
$T_1 = 288.15$ K; $T_3 = 1650$ K; $p_{1i} = 0.99\cdot10^5$ Pa;
$p_2 = 2\cdot10^6$ Pa; $p_{3i} = 1.95\cdot10^6$ Pa; $p_4 = 1.02\cdot10^6$ Pa;
$\eta_{iC} = 0.90$; $\eta_{iT} = 0.89$; $\eta_{CC} = 0.99$;
$m_T = 0.2537$; $m_C = 0.2857$;
the following result was achieved:

$$\eta_{i\mathrm{GT}} = 0.35686.$$

If the internal efficiency of the compressor and the turbine was only 0.01 lower (other parameters are the same), the following result was achieved:

$$\eta_{i\mathrm{GT}} = 0.34413.$$

This means that the gas turbine relative efficiency decreased by about 3.57%.

The internal power of the gas turbine depends on:

$$P_{i\mathrm{GT}} = \dot{m}\cdot l_{i\mathrm{GT}} \tag{2}$$

Due to fouling, the air mass flow and internal specific work of the gas turbine decrease. We calculated this phenomenon in two situations, normal (without fouling) and with fouling, for the same data above. Additional required data included: $\dot{m} = 85$ kg/s; $c_{p\mathrm{AIR}} = 1.005$ kJ/kgK; $c_{p\mathrm{EG}} = 1.10$ kJ/kgK; $\beta = 1.02$:

$$l_{i\mathrm{GT}} = l_{iT} - l_{iC} = \\ = c_{p\mathrm{EG}}\cdot T_3\cdot\beta\left[1-\left(\frac{p_{3i}}{p_4}\right)^{-m_T}\right]\cdot\eta_{CC}\cdot\eta_{iT} + \\ - c_{p\mathrm{AIR}}\cdot T_1\left[\left(\frac{p_2}{p_{1i}}\right)^{m_C}-1\right]\frac{1}{\eta_{iC}} \tag{3}$$

According to the results from equation (3), $l_{i\mathrm{GT}} = 421.9$ kJ/kg under normal conditions and $l_{i\mathrm{GTF}} = 407.3$ kJ/kg with fouling. This means 3.46% lower internal specific work. If the mass flow decreases by 1% of its nominal value, the internal power will decrease by about 4.45%.

It is easy to estimate the change if the network ratio (NWR) is known near the nominal point for the gas turbine specified.

The possible power reduction of gas turbines due to fouling can reach 7–13% (Figure 4) (if the ambient temperature is 40°C, the drop in power is greater, between 8% and 17%) for a gas turbine power of up to 50 MW (Meher-Homji, Bromley & Stalder, 2013). For a power within the range of 50–300 MW, it stabilizes at 7–9%. If the NWR is lower, the sensitivity to fouling is higher, i.e., the power reduction is greater (quickly increasing the power required for the compressor). Figures 4–6 were prepared based on the same gas turbine as ref. (Meher-Homji, Bromley & Stalder, 2013).

Equation (4) presents the linear approximation (Figure 4) (correlation coefficient $R^2 = 0.485$) of percentage power reduction (PPR):

$$\mathrm{PPR} = -17.8\cdot\mathrm{NWR} + 17.2 \tag{4}$$

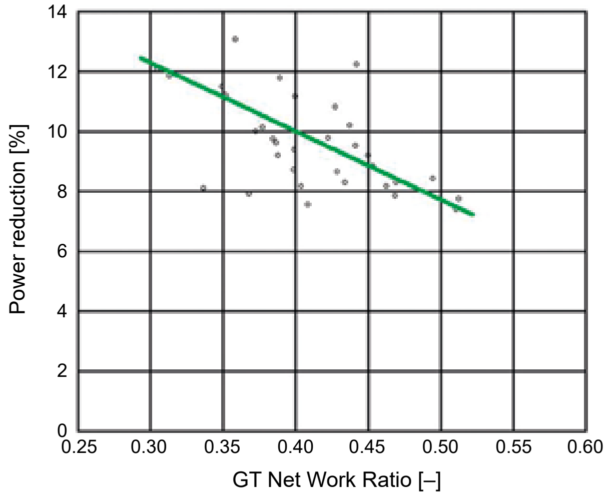


Figure 4. Gas turbine power reduction due to fouling vs. network ratio

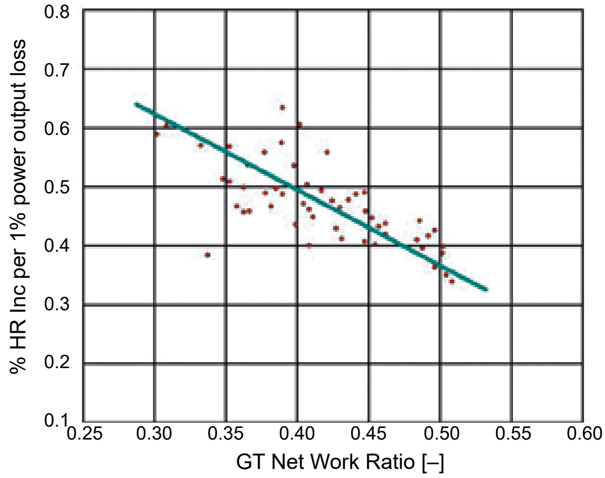


Figure 5. Percent increase of the heat rate as an effect on power output reduction due to fouling at 1% vs. network ratio

This is the first of two proposed approximations (equations (4) and (5)). The heat rate is the next important parameter that increases due to fouling. The percent increase in the heat rate versus power output reduction at 1% is presented in Figure 5 (Meher-Homji, Bromley & Stalder, 2013). In simpler terms, a 1% reduction of power translates into around 0.5% increase in the heat rate – in other words, it increases the fuel consumption at the same level.

Equation (5) presents the linear approximation (Figure 5) (correlation coefficient $R^2 = 0.749$) of the percentage heat rate (PHR):

$$\mathrm{PHR} = -1.1 \cdot \mathrm{NWR} + 0.94 \tag{5}$$

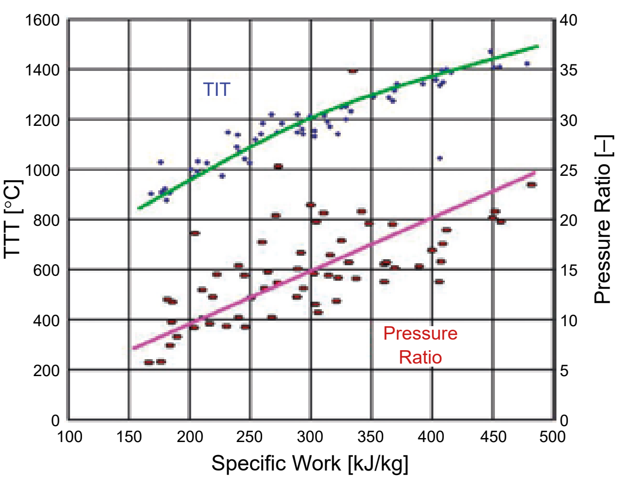
This is the second proposed approximation. A juxtaposition of gas turbine parameters (for the selected 92 GTs with different types and applications) shows the most important parameters in the dependency of specific work and power, which are presented in Figure 6. It allows the estimation of whether the gas turbine data is correct or incorrect. There are some propositions of estimation of the dependencies without the approximations and propositions of equations.

The heat rate depends on the thermal efficiency of the gas turbine in accordance with:

$$\mathrm{HR} = \frac{3600}{\eta_{i\mathrm{GT}}} \left[\frac{\mathrm{kJ}}{\mathrm{kWh}}\right] \tag{6}$$

The specific fuel consumption (SFC) depends on an additional parameter – the low heat value (LHV) of the fuel used. It is presented in the following dependence:

$$\mathrm{SFC} = \frac{3600}{\eta_{i\mathrm{GT}} \cdot \mathrm{LHV}} \left[\frac{\mathrm{kg}}{\mathrm{kWh}}\right] \tag{7}$$



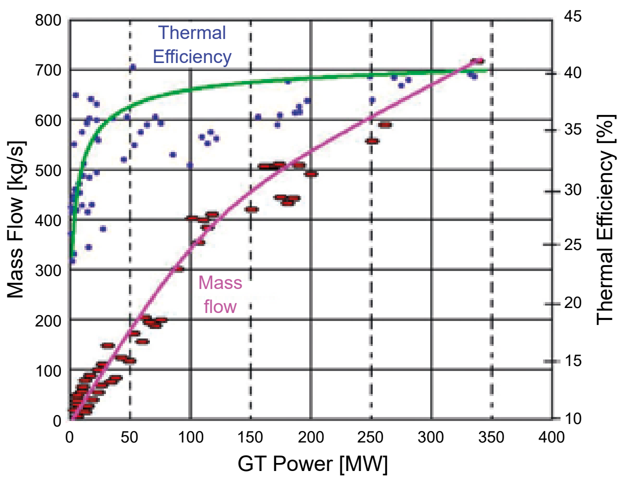


Figure 6. Temperature inlet to the turbine (TIT) and pressure ratio dependence on the specific work of different 92 gas turbines (left side) and mass flow with thermal efficiency as a dependency on power (right side)

Dependence of gas turbine performance on external and internal parameters

The accessible power of gas turbines should be adjusted to a level of maximum acceptable temperature inlet to the turbine (TIT). The GT output depends on the installation effects, especially on pressure losses in the inlet duct, in the combustion chamber, and the exhaust gases outlet. According to the manufacturer's requirements, for an MT30 with a maximum 4 inch (100 mm) water gauge (w.g.), a nominal inlet loss and 6 inches (150 mm) of nominal exhaust loss are acceptable (Jeffs, 2003; Edge, 2016). As an example, if the pressure drop increases to 400 mm w.g.:

- On the inlet side, the PPR decreases by about 5%, and the SFC and PHR increase by about 0.9%;
- On the exhaust side, the PPR decreases by about 1.7%, and the SFC and PHR increase by about 1.1%.

An example of the effect of installation pressure losses in the MT30 on the power and SFC is presented in Figure 7 (Edge, 2016; Herdzik & Cwilewicz, 2017).

A 1°C change in the ambient temperature resulted in a 0.55–0.9% change in the gas turbine power (higher temperature – lower power and *vice versa* – inversely correlated). The air temperature may be decreased through the fogging process in the inlet to the GT (Domachowski & Dzida, 2019). The power depends proportionally on the ambient pressure (higher pressure – higher power). Every 100 m change in elevation (below or above sea level) changes the gas turbine power by about 0.11% (i.e., a higher location decreases power) (Yang & Xu, 2014; Walsh & Fletcher, 2004). Because the nominal parameters of the GTs are given under ISO conditions, this should be recalculated if the ambient parameters are different.

Methods section. Operation and maintenance of the MT30 gas turbine

Following the information from the GT manufacturer, the maintenance of the MT30 requires less than 90 min per week (Jeffs, 2003; Edge, 2016). Only "level 2" maintenance is required, which can usually be performed by the GT operator. Because the MT30 has a modular design, the overhaul of the gas turbine is simpler than that of a diesel engine. Due to lower labor expenditure, the number of operators (vessel's crew) may be lower.

The hot turbine casing is cooled by spraying it with water mist. Due to the risk of damage, the size of water mist droplets and water flow must be controlled (Edge, 2016). When the ambient temperature is low (< 5°C), the inlet guide vane may become iced, or other problems with inlet air parameters might arise (high air humidity). In this case, the air bleed from the third stage of the high-pressure (HP) compressor is available with a flow constraint of up to 4 kg/s (Edge, 2016). It should be mentioned that IGV adjustments have not been considered in this paper.

The MT30 is also prepared for different applications as a prime mover on vessels. The MT30 is a twin-shaft turbine whose compressor is driven by a high-pressure turbine. The low-pressure turbine is the propulsion engine. In the case of driving a fixed-pitch propeller, the work of the GT requires a different output rotational speed. The basic data of the MT30 are presented in Table 1. Part of these data

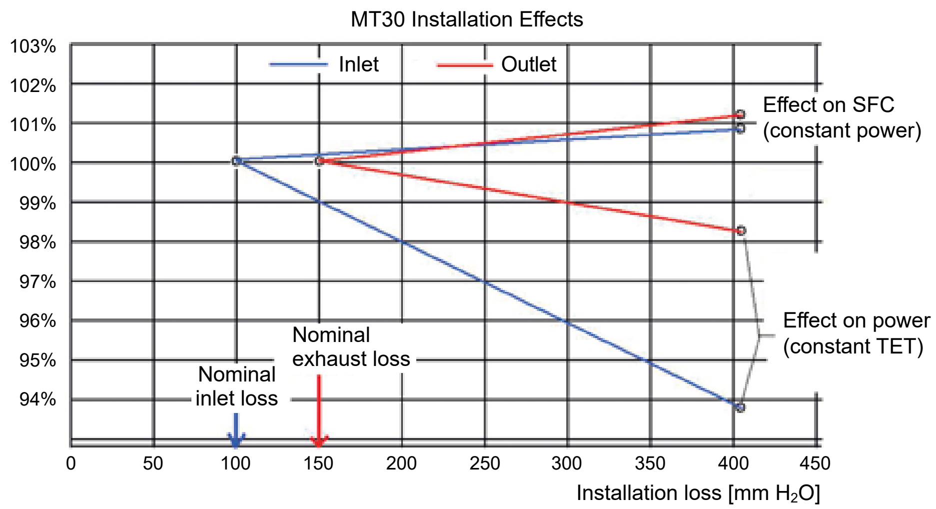


Figure 7. Indicative effect of installation pressure loss on the SFC and power of a MT30 gas turbine

comes from sea trials (Edge, 2016), and the others are calculated when the turbine was operated with the same fixed-pitch propeller characteristics.

Table 1. Basic data of the MT30 working on propeller characteristics (under ISO conditions) on the fuel of a standard LHV 42,707 kJ/kg

Power [MW]	Power turbine speed [rpm]	SFC [kg/kWh]	Inlet flow [kg/s]	Exhaust flow [kg/s]	Exhaust gas temperature [K]
40	3418	0.216	120	122	759
36	3300	0.220	115	117	742
32	3173	0.225	110	112	728
28	3035	0.231	105	106	711
24	2883	0.240	99	100	695
20	2713	0.251	93	94	679
16	2518	0.266	85	86	661
12	2288	0.290	77	78	641
8	1999	0.345	70	70	619
4	1586	0.473	57	57	593
Idle 0.7	920	1.089	33	33	560

The operating envelope is shown in Figure 8. In the diagram, the basic area of the operating envelope (green color) can be seen between two different propeller characteristics: the light (minimal power demand) and the heavy one (maximal power demand). The most realistic load characteristics in the vessel operation in good sea conditions were the propeller characteristics during sea trials.

Results section. Deterioration processes due to fouling of the MT30 gas turbine

It is possible to measure the theoretical maximum power from the GT to the nominal temperature inlet to the turbine (TIT). Next, a recalculation of the received power should be done on the ISO

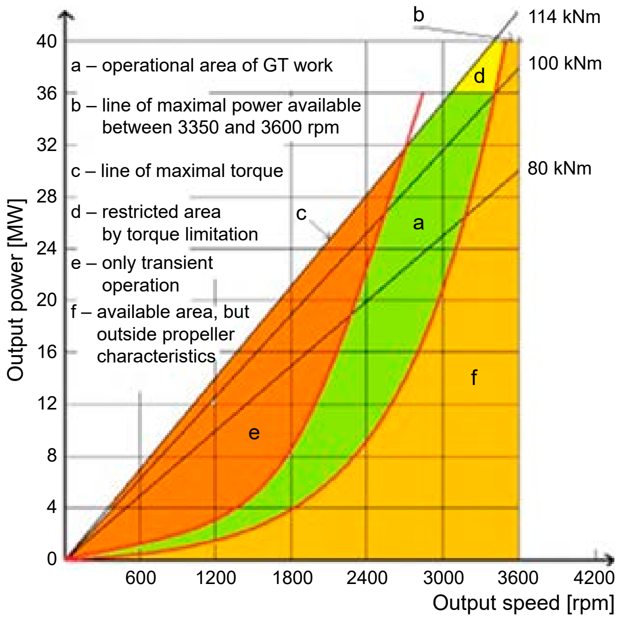


Figure 8. MT30 operating envelope (Herdzik & Cwilewicz, 2017)

conditions to compare it against the nominal parameters of a healthy GT given by the manufacturer. The difference between the nominal power of a GT (as 100%) and the received power on the ISO conditions provides the level of the GT power deterioration due to fouling and other processes, such as deterioration of the GT (irremovable), the cleanliness of air filters, and the ambient air parameters (especially air humidity or fog) impacting the pressure drop on filters. The model of power deterioration of the GT during its operation is shown in Figure 9. It was obtained by off-line washing and air filter cleaning every 500 h (±20 h) of the GT operation at different loads. This is an offline washing schedule for the MT30 in the marine propulsion application. The MT30 was in operation for the first two years after

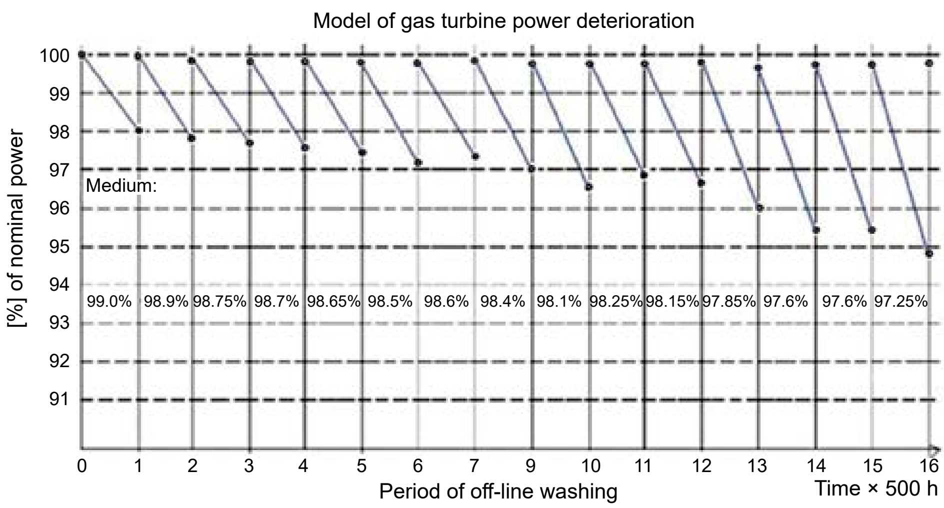


Figure 9. Model of MT30 off-line washing procedure (the results were obtained in 2018–2019)

its commissioning. The observed deterioration was rather small.

Only two points are known: the accessible power of the GT before stopping, and after the washing procedure and starting. The model suggested linear deterioration between points and the same period between washings. A linear change (the simplest estimation) of the possible output between these two points was used, and the following result is an arithmetic mean. The relative medium accessible power of the 15 periods (about 7,500 h) presented was 98.287%, and the power deterioration reached 1.713%.

The deterioration of the gas turbine power depends on other factors, but fouling is the most important one because, during washings, only this one can be removed. The turbine deterioration from component failures is a continual process that leads to the repair and replacement of some components.

Fouling leads to increased fuel consumption, resulting in additional turbine operation costs. For the MT30, the accuracy of the direct measurement of fuel consumption was too low, as it was more difficult due to the time required to stabilize the load and the need to measure two parameters: momentary fuel consumption and actual power to calculate the heat rate, specific fuel consumption, or thermal turbine efficiency. These parameters are not known for the turbine under analysis. Taking into consideration the conclusion from Figure 5, it has been estimated that the average fuel consumption as a percentage increased the power turbine deterioration by 50% (for NWR = 0.4). This accounted for about 0.66% of the nominal power of the MT30. Taking into account the time of the GT operation at 5,000 hours per year and the fuel price of marine diesel oil with a sulfur content below 0.1% as $700/mt (according to marine fuel prices in 2019–2020), the annual cost of fouling of the MT30 (nominal power at 36 MW) has been estimated as US$ 180,000 (only additional fuel cost) and about US$ 120,000 for mechanical energy not produced (at the cost of 0.09 $/kWh). In total, this constituted US$ 0.3 million per year of the MT30 operation.

For comparison, the annual cost of compressor fouling for three heavy-duty turbines is shown in Table 2 (Bromley, 2012). The cost was estimated only for compressor fouling. The additional cost due to power and thermal efficiency deterioration of the gas turbine due to compressor and turbine fouling was significant.

Table 2. Annual cost of compressor fouling estimated for three heavy-duty gas turbines

GT type	Fr7EA	Fr7FA	V94.3A
Power output, clean [MW]	85.0	172.0	285.0
Power o/p at end of a period [MW]	80.8	163.4	270.8
Net cost of degradation [$MM]	1.268	2.685	4.556

Final remarks

The understanding, measurement, and control of fouling and the deterioration in the performance of a gas turbine are imperative for the operator. Due to the complex geometry of turbine blades and different operating and ambient conditions, it is very difficult to predict fouling phenomena. Fouling rates can vary between types of gas turbines, the specificity of the turbine analyzed, the place of the turbine's operation, environmental conditions, etc. A combination of off-line and on-line washing usually provides the best results for fighting fouling, which is a very common and insidious operating phenomenon. The monitoring of turbine performance can help optimize the turbine (mainly compressor) washing regimes. The final result should be improving the gas turbine plant's profitability. The measurement of the GT's output at the maximum available temperature TIT allows for the estimation of the GT's power deterioration. Two linear equations have been proposed, showing the dependence between the power reduction percentage and the network ratio, and another dependence between the heat rate change percentage and the network ratio. By knowing the network ratio, it is possible to estimate the increase in the total and specific fuel consumption and, after simple calculations (using equations (6)–(7)), the actual heat rate (HR) and GT thermal efficiency. This is the most important conclusion of this research. The profit loss during gas turbine operation accounted for 1–10% of the total fuel consumption costs. The next conclusion is that it provided US$ 10,000–20,000 annually per 1 MW of the GT nominal power for just a 1–2% decrease in the GT output. The discovery of an effective method to prevent GT deterioration is the most important recommendation for any future research by all participants in the GT field, including the author.

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