GAS TURBINES FOR ENERGY NETWORK SYMPOSIUM
BANFF, ALBERTA, CANADA
OCTOBER 2019

19-GTEN-206

THE EFFECT OF AIR FILTRATION ON GAS TURBINE PERFORMANCE DEGRADATION – ISO 16890 AND ITS APPLICATION TO REAL ENGINE DATA

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Keywords: *Gas Turbine, Air Filtration, ISO 16890, Real Engine Data, Performance Degradation*

Abstract

The degradation of gas turbine power output and compressor efficiency over time is strongly influenced by the amount and composition of particles entering the compressor. This amount is on one side affected by the chosen air filtration layout, i.e. by filter classes, filter configuration, volume flow per filter etc. and on the other side by the size distribution, mass and chemical composition of particles in the ambient air.

The introduction of the new global standard ISO 16890:2016 [1] brought a different approach to evaluate the filtration efficiency as a basis for filter classification: filter efficiencies will be determined with regard to separation efficiencies for particulate fractions PM1, PM2.5 and PM10, which are also used as evaluation parameters by the WHO (World Health Organization) and environmental authorities.

This paper describes the correlation between power output, respectively compressor efficiency degradation, the performance of installed air filters according to the new ISO 16890 standard and the concentration and mass distribution of dust particles at the gas turbine's specific location. Such a correlation in combination with public available particle concentration data and Freudenberg's e.FFECT software (electronic Freudenberg Filter Efficiency Calculation Tool) allows determining the economically best filtration layout for any given power plant.

Introduction

Since the turn of the millennium, air filters of the EPA classes according to the standard EN 1822 [2] (EPA = Efficient Particulate Air) have become increasingly popular for the combustion air filtration of gas turbines. This is especially true in case of multi-stage, static filter systems. However, there are also clear tendencies towards the use of higher-separation filters in so-called pulse-jet systems.

High-efficiency filters allow only small amounts of dust to penetrate into the compressor of the turbine, thus reducing the performance loss of the turbine caused by fouling. However, better particle separation using the same number of filters usually entails increased pressure losses via the intake system, higher initial costs for the air filters or shorter filter life. One way of counteracting these problems is to increase the number of filters. The disadvantage of this approach is that investment costs are increased for new units as well as for retrofits of existing air intake systems. In most cases, however, the advantages of improved filtration outweigh the disadvantages mentioned, as previously shown in [3]. Advanced air filters with lower pressure drops and increased dust storage capacity make an important contribution in this regard.

The relationship between the dust mass entering the compressor of a gas turbine over a period of time and the loss of turbine performance it causes can serve as an important parameter in selecting the most economical sequence of filter classes in multi-stage systems. Because air filters always separate a percentage of particles, site-specific dust concentrations affect the dust load entering the compressor. A high concentration of dust at a specific site means that a correspondingly higher dust load will be transported into the turbine.

To calculate the actual dust load per unit of time reaching the compressor in relation to the filter system in place, annual average values for PM2.5 and PM10 concentrations – as well as the ISO 16890 filter test standard in a somewhat expanded form – can be used. Based on a mass distribution of the dust in the ambient air, a specially designed software named e.FFECT calculates how much dust mass per unit of time passes through the filter system.

During a major field study [4] data was systematically collected from a variety of power plants around the world with different gas turbines. The aim was to establish a relationship between the filter classes of the installed air filters and the power output as well as the compressor efficiency degradation of the turbines. Different configurations of air filter classes were used at these sites and the performance loss of the turbine as a result of fouling was quantified.

Annual average values of PM2.5 and PM10 at the locations of the above mentioned gas turbines can be used for calculating the dust mass transported into the air intake systems of the turbines each year. The resulting dust concentrations on the clean air side of the filter systems were correlated with the turbines' performance degradation for each of the investigated filter configurations. These calculations ultimately enable the economics of filter systems to be assessed. This is done by synthesizing turbine performance degradation due to fouling, performance loss of the turbine as a result of the pressure drops over the filters, and the cost of the filters. With the help of the computer program e.FFECT, the most economical filter configuration can be determined for any given site.

Dust Concentration in Ambient Air Expressed As PM1, PM2.5 and PM10

Wherever a turbomachine is located, the dust concentration varies depending on the weather and the season. Even over the course of a single day, it is perfectly normal to see fluctuations. In the event of an atmospheric inversion, the dust load at the observed location will be above average. Other influencing factors are temporarily occurring winds that can, for example, transport Saharan dust to Central Europe.

In Southeast Asia, exceptionally dusty conditions are a regular occurrence. This is due to the practice of slash-and-burn on oil palm plantations at remote locations. In Singapore, for example, the authorities are directing power plants to be prepared for these extreme loads and to stockpile sufficient spare filters. The serious smog events in the metropolises of the Chinese East coast are well known, but Indian cities experience regular extreme particulate matter pollution as well.

The mass concentrations PM1, PM2.5 and PM10 are usually used as a unit of measurement of particulate matter or ‘PM’. In scientific terms, PMx is the mass concentration of particles passing through a size selective separator with a 50% separation efficiency for particles with an aerodynamic diameter of x µm. Figure 1 illustrates the definition of PM1, PM2.5 and PM10. The reason why these three dust fractions were selected is related to the respective extent to which they penetrate the respiratory tract in humans.

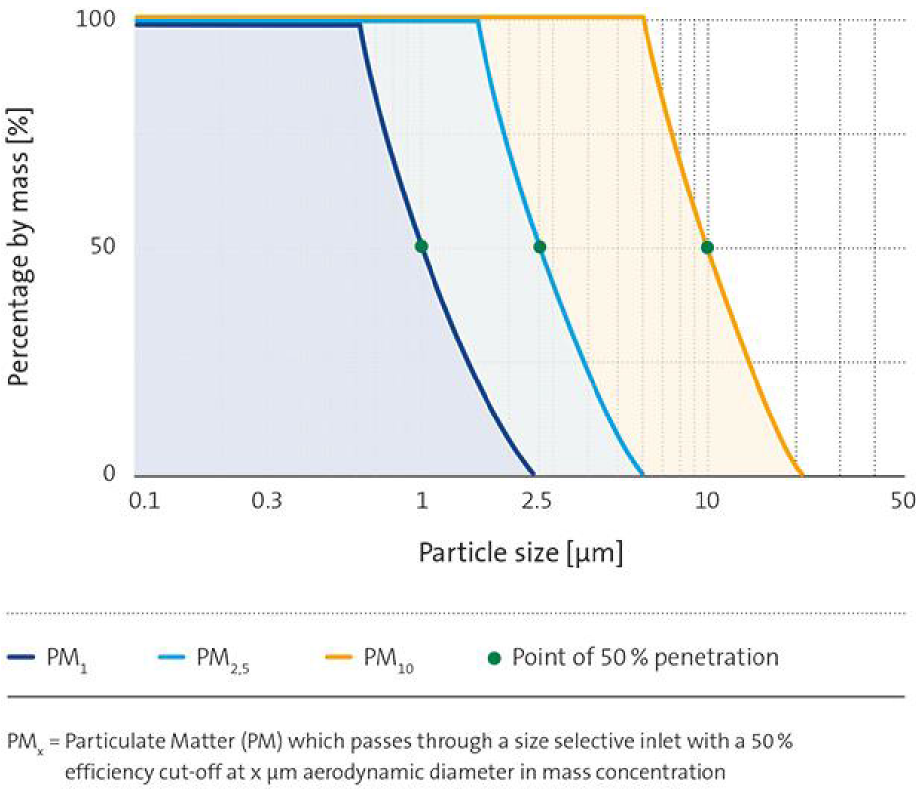

Figure 1: Visualization of the mass concentrations PM1, PM2.5 and PM10 as areas below the respective curve

As can be clearly seen from this illustration, PM1 and PM2.5 are subsets of PM10, while PM1 is in turn a subset of PM2.5.

PM annual average values are good indicators for characterizing the dust load at the location of a turbomachine because filter lifetimes cover a similar time span. Therefore peaks and seasonal influences are averaged out. The consideration in comparable time scales is reasonable for a reliable calculation. Figure 2 gives an indication of typical magnitudes of mean dust concentrations at a variety of differently characterized locations.

For the following considerations, PM10 should be simplified to denote the mass concentration of all particles smaller than 10 µm, PM2.5 the mass concentration of all particles smaller than 2.5 µm, and the same principle applied for PM1. Accordingly, the dimension of PMx is µg/m³.

REGION	RESIDENTIAL AREAS	COUNTRY AREAS	LIGHT-INDUSTRY AND URBAN AREAS	HEAVY-INDUSTRY AREAS	URBAN HIGHLY POLLUTED AREAS	COASTAL REGIONS AND OFFSHORE	DESERT AREAS	ARCTIC AREAS	TROPICAL AREAS
Ann. average PM10 [µg/m³]	20−25	10−20	25−30	25−50	> 50	10−30	10−5,000	10−30	10−50
Ann. average PM2,5 [µg/m³]	10−15	5−10	15−30	15−40	> 30	5−20	10−1,000	5−20	5−30

Figure 2: Typical mass concentrations of PM2.5 and PM10 dust at differently characterized locations

Typical Mass Distribution Densities of Dust in the Ambient Air

Knowing the mass distribution density of the dust is helpful to choose the most suitable filter system for a turbine site. The mass distribution density shows which particle sizes make the highest or lowest contribution to the total dust mass. Figure 3 shows typical distribution densities in predominantly urban or predominantly rural regions. Both curves share a bimodal distribution with maximums at approx. 0.3 µm and 10 µm. The particle fraction around 0.3 µm is caused by humans and is generated by combustion processes, industrial production, motor traffic, etc.

The fraction around 10 µm comes from natural sources such as the erosion of the earth's crust, pollen or volcanic eruptions. This also explains why in urban areas the peak around 0.3 µm is higher, while in rural areas 10 µm particles dominate.

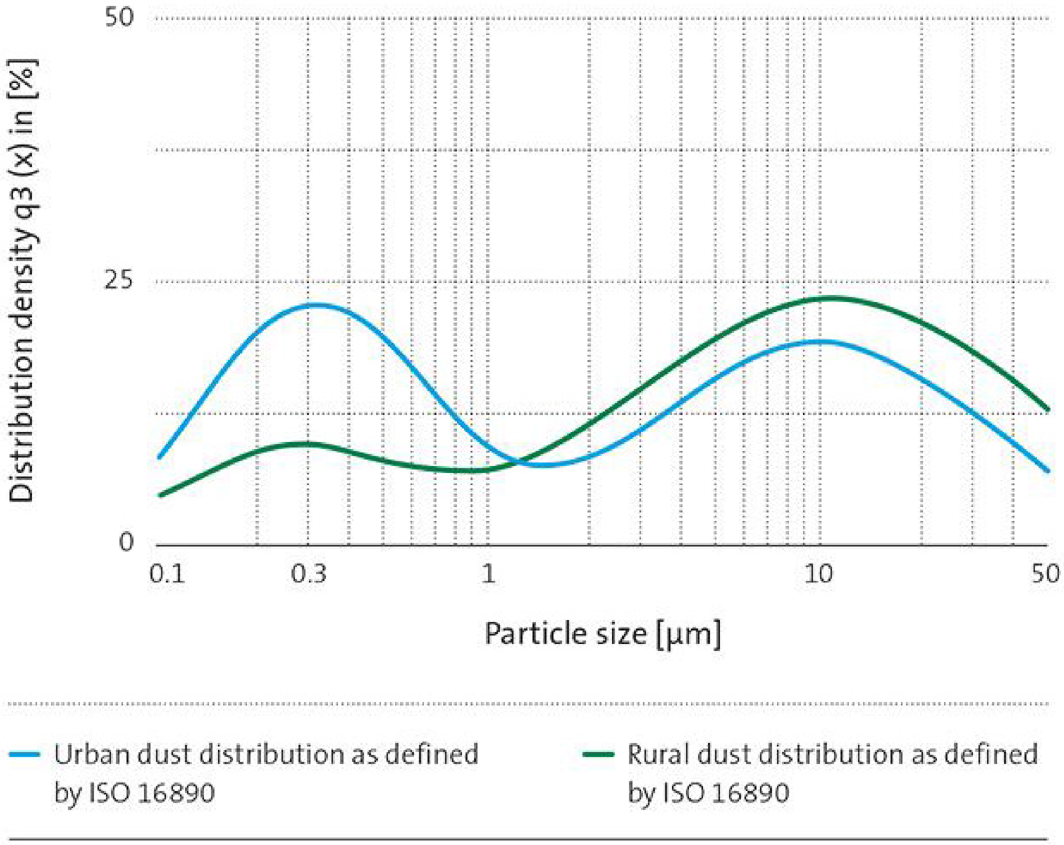

Figure 3: Typical mass distribution densities of dust in urban and rural areas.

A filter system should be adapted to the particle distribution type of the respective location. For example, a high load of particles around 10 µm should be reflected in the choice of suitable coarse dust filters. However, the same coarse filters could remain relatively ineffective at locations with a high dust load in the size range around 0.3 µm, allowing most of the dust to pass through to the second filter stage. In such a situation, this second filter stage may then have an unexpectedly short lifetime.

Calculation of the Dust Ingress into the Gas Turbine

At the end of 2016, the ISO 16890 air filter test standard became valid worldwide. As a result, the methodology for evaluating the separation efficiency of a filter is now based on the consideration of the particle size spectrum between 0.3 µm and 10 µm. The integration of this range of particle sizes forms a key difference to the previous and often used EN 779 [5] standard, which only considered a single particle size of 0.4 µm in its testing procedure.

The new ISO 16890 standard also incorporated the findings of numerous investigations into used filters. While the synthetic ASHRAE dust [6] used in the EN 779 testing procedure leads to a significant increase in the separation efficiency of a filter during the test procedure, atmospheric dust stored in filters has barely any influence on separation behavior. Contrary to widespread opinion, air filters loaded with atmospheric dust did not generally show any appreciable increase in separation behavior over time. In preparation for ISO 16890, therefore, the conclusion was drawn that filters should only be evaluated when new. Compared to EN 779, testing the filters in new state achieves an improved and conservative correlation between filter data, determined in the laboratory, and actual real-life performance during operation.

The particle-size-related separation levels are used as filter-specific input data. This so called fractional collection efficiency indicates what percentage of a given particle size is separated by the filter. The sum of fractional collection efficiency and penetration for each particle size equals 100 %. The fractional collection efficiency of a filter is measured according to ISO 16890 on a standardized test rig with artificially created aerosols (DEHS droplets, potassium chloride crystals) without dust loading on the filter.

If the PM1, PM2.5 or PM10 values for a specific location are known, this method can be used to calculate how much dust will enter and pass through the filter per unit of time.

The e.FFECT software uses a dust mass distribution at the location of the turbine and the fractional efficiency of the filters in each stage. The mass distribution after the first filter stage is the input for the second stage and so on. In addition to ISO 16890 the particles smaller than 0.3 µm and larger than 10 µm have been included in the assessment.

Using the software, it is possible to calculate how much dust reaches the compressor at a set location and over a fixed time period for different filter combinations using given PM1, PM2.5 or PM10 values and mass flow rates through the turbine.

Relationship Between Filter Efficiencies TO EN 779, ISO 16890 and Performance Degradation Due to Fouling

ASME Paper 2016-56292 [4] showed how the use of filters of different classes affected the performance degradation of the investigated gas turbine as a result of fouling on the compressor blades. The most important results are shown in Figure 4.

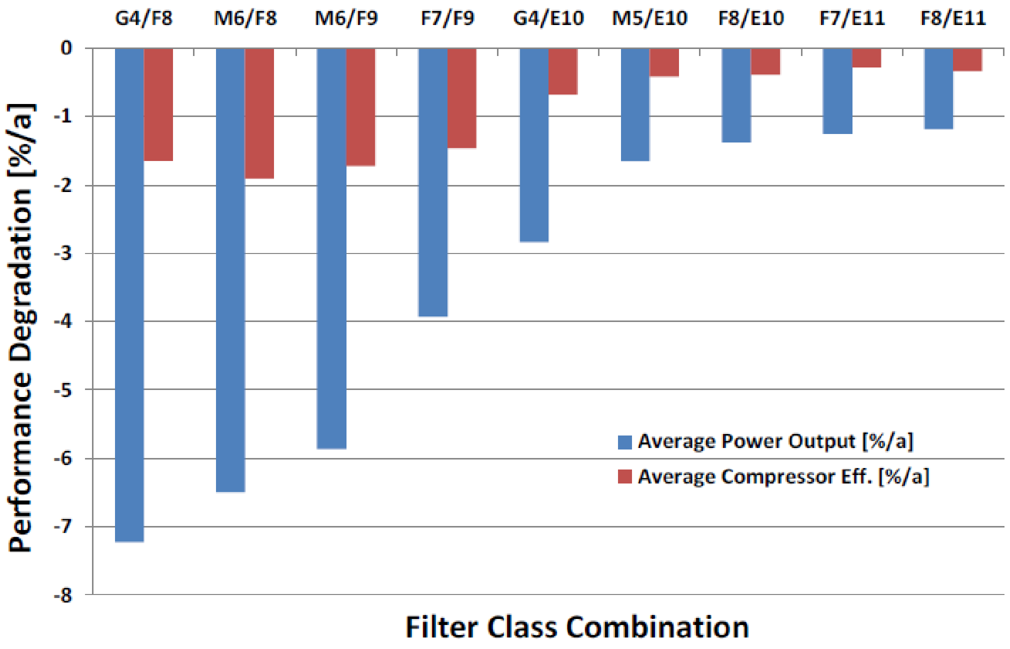

Figure 4: The effect of different filter combinations on the performance loss of different gas turbines [4]

For this survey real world engine data were recorded over several years, taken at different gas turbines around the world with 50 filter cycles summarized in 20 filter configurations. For the evaluation of the power degradation at one plant, the operating time was considered between two compressor offline washings, filter exchanges and/or major inspections (whatever came first). Because the recorded operating time at the different gas turbines varied but the correlation between operation hours and power degradation is linear in the considered operating period as [4] showed, all recorded degradation values were standardized to 8760 operating hours.

The reference has been made in [4] to filter classification according to the old EN 779 test standard as well as to the EN 1822 standard and not to the new ISO 16890 standard. For ease of comparison, Figure 5 (based on [7]) shows side by side the classification of air filters according to EN 779 / EN 1822 and ISO 16890.

It is not possible to create a general conversion table from classes defined according to EN 779 and the new ISO 16890. The main reasons are that the EN 779 test procedure was restricted solely to the 0.4 µm particle size and included the load of ASHRAE dust in the classification. In contrast, ISO 16890 includes the size range between 0.3 µm and 10 µm and rates the filter without dust loading.

EN 779:2012 EN 1822:2009	ISO 16890 – RANGE OF ACTUAL MEASURED AVERAGE EFFICIENCIES		
FILTER CLASS	ePM_1	$ePM_{2,5}$	ePM_{10}
M5	5–35 %	10–45 %	40–70 %
M6	10–40 %	20–50 %	60–80 %
F7	40–65 %	65–75 %	80–90 %
F8	65–90 %	75–95 %	90–100 %
F9	80–90 %	85–95 %	90–100 %
E10	90–97 %	95–98 %	98–100 %
E11	95–98 %	97–99 %	99–100 %

Figure 5: Overview about filter classification to EN 779 respectively EN 1822 versus the actual measured efficiencies according to ISO 16890 (based on [7] and own data)

Quantitative Relationship Between the Dust Mass in the Compressor and Performance Degradation Due to Fouling

In a new approach the data of the survey were correlated with the e.FFECT software and filter efficiencies according to ISO 16890. The PM2.5 and PM10 concentrations for the respective locations over the survey period are known.

The e.FFECT software calculates the amount of dust mass entering the turbine per time period using the respective filter combination. A relationship is established between the calculated dust masses and the performance degradation of the gas turbine.

This new approach provides a basis for the description and prediction of the combustion air quality's impact on the performance degradation in gas turbines and - as a further step - on the economical operation of the unit. The results of this study are visualized in Figures 6 and 7, where the power degradation is plotted vs. the dust concentration in the combustion air after the final filter stage. Operation data for the configurations with last stage filter classes of F8 (red), F9 (orange), E10 (blue) and E11 (green) and various pre-filter classes were evaluated. Two-stage (circles) filtration as well as three-stage (triangles) filtration was considered. Figure 6 shows the total power loss of the gas turbine while figure 7 shows a corrected power loss. Because the power loss of a gas turbine is not exclusively caused by contamination and wear effects, but is also partly due to the flow resistance of the filter system, the latter loss was deducted for Figure 7. For the power loss correction due to pressure drop over the filter system 0.13 % power degradation per 100 Pa pressure drop was applied, as calculated with heat balances for F-Class gas turbines. To be conservative the final pressure drop at the end of the filter life cycle was used. The strong correlation between clean gas particle concentration and power loss of the gas turbine underpins the applicability of the e.FFECT software at all different locations of the survey.

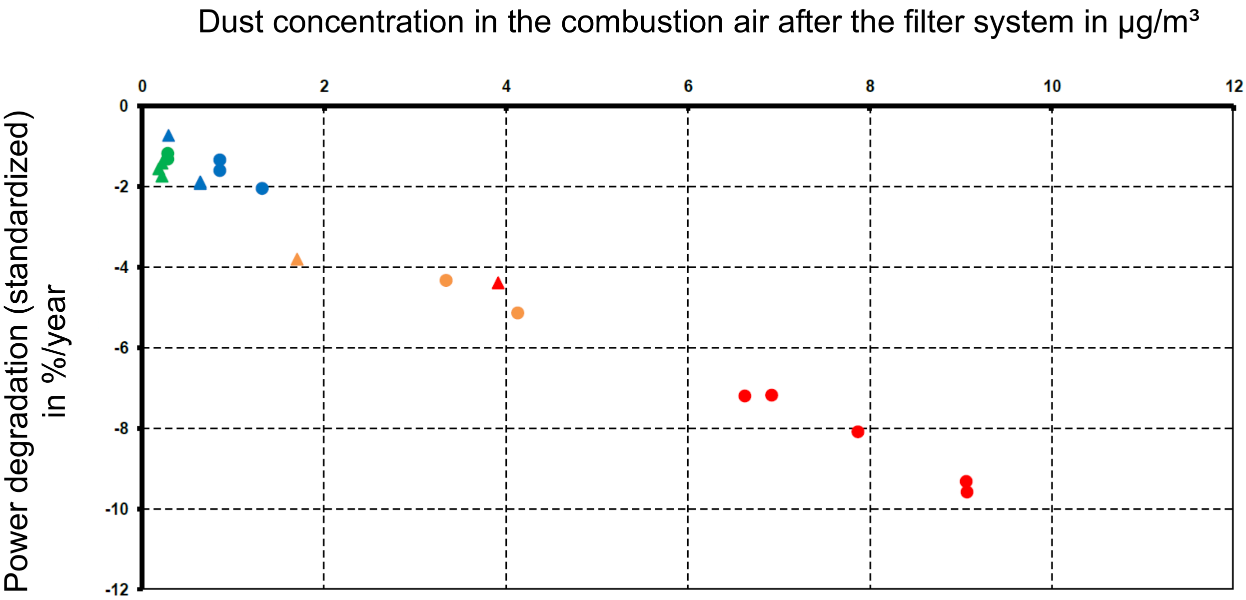

Figure 6: Dust concentration in the combustion air after the filter system vs. power degradation for real engine data standardized to 8760 operating hours (one year)

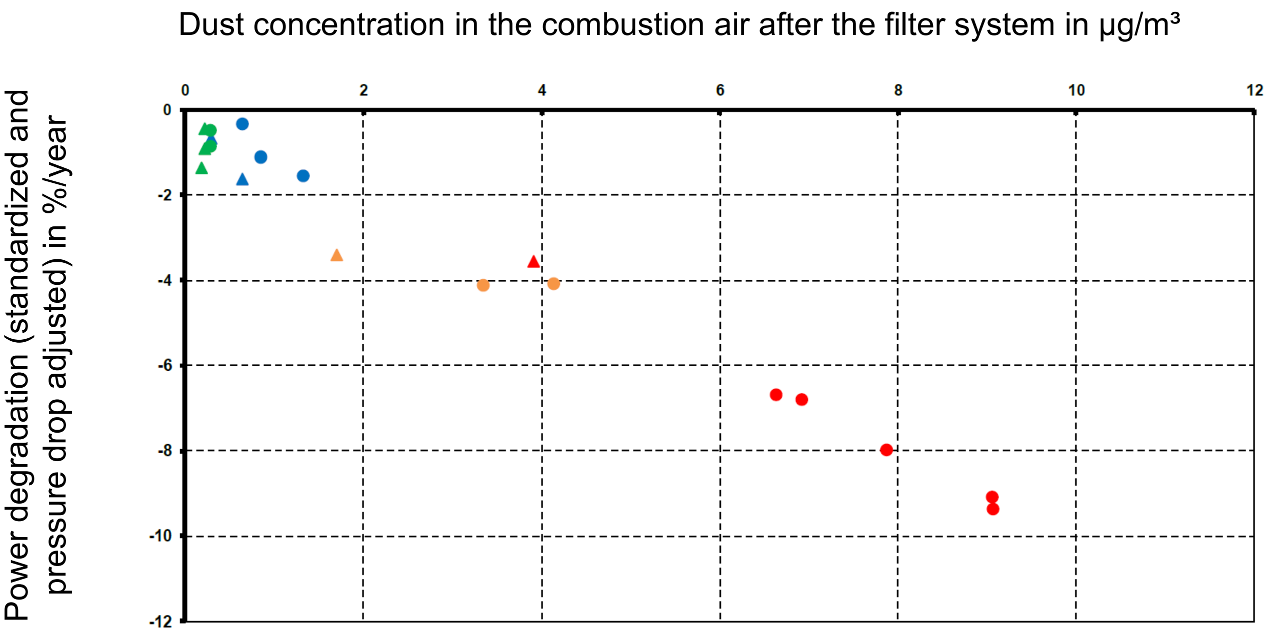

Figure 7: Dust concentration in the combustion air after the filter system vs. power degradation for real engine data standardized to 8760 operating hours (one year) and pressure drop adjusted

Looking at both figures, it is noticeable that with increasing dust concentration in the combustion air after the filter system, the power loss of the gas turbine increases. When comparing the different filter configurations, systems with final stage filters of class F8 or F9 have significantly higher clean air concentrations than systems with filters of classes E10 or E11. These higher dust concentrations are reflected in higher power losses of the gas turbine. A comparison of Figures 6 and 7 shows that the power loss of the gas turbine due to the pressure drop plays a subordinate role compared to the power loss due to higher dust concentrations in the combustion air. The pressure-drop-related power losses are higher for more separation-efficient filter classes such as E10 or E11 than for less separation-efficient classes such as F8 or F9, but these do not exceed the one percent mark. The power loss due to lower dust separation, on the other hand, is up to eight percent.

The location-dependent configuration of the filter system thus has an immense influence on the power loss of the gas turbine, whereby the dust concentration on the clean air side of the filter system is dominant. Therefore, when selecting a filter combination, the ambient air quality should always be taken into account and a low particle concentration in the combustion air should be aimed for.

Conclusion

The application of the new standard ISO 16890 to the data of the studied units reveals to be a very good basis for the evaluation of gas turbine performance degradation in correlation with clean gas concentrations behind the air intake filter systems. The power loss of a gas turbine is dominated by the separation efficiency of the filter system. The pressure drop of the filter system, on the other hand, plays only a minor role even with high efficiency classes and multi-stage systems. To achieve the most economical operation of the gas turbine, the location-dependent outside air particle concentration should be determined when designing a filter system and a low particle concentration in the combustion air after the filter system should be striven for.

Nomenclature

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASME	American Society of Mechanical Engineers
DEHS	Diethylhexylsebacat
e.FFECT	electronic Freudenberg Filter Efficiency Calculation Tool
EN	European Norm
EPA filter	Efficient Particulate Air filter
Eurovent	Europe’s Industry Association for Indoor Climate (HVAC), Process Cooling, and Food Cold Chain Technologies
ISO	International Organization for Standardization
PM	Particulate Matter

Acknowledgments

The authors would like to thank their companies, Freudenberg Filtration Technologies SE & Co. KG and Ansaldo Energia Switzerland Ltd. for the time and infrastructure provided in order to realize the analyses and this paper.

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