

# GAS COMPRESSOR UNIT PERFORMANCE MONITORING USING FUZZY CLUSTERING

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A. Suomilammi . J. Leppäkoski¶

## Abstract

This paper **concerns** development and implementation of an on-line performance monitoring system of a natural gas compressor unit. **The system** can be used to monitor and evaluate the operation and performance of a gas compressor. The system was built for the use of natural gas network operators and maintenance personnel of Gasum Oy in Finland. This paper focuses on how the reference values of a compressor performance can be obtained if reference is not available. A short overview is made also to the capacity loss due to the gas compressor degradation, compressor operating map and their normalization due to changing process conditions.

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**H**istory data of pressure-, temperature-, and rotational speed measurements of the gas turbine's axial compressor were collected in order to create the reference value for performance estimation. The monitoring system has to produce reference or expected values of the prime performance parameters in order to reliably evaluate the performance and condition of the compressor. The reference value in this case is the polytropic efficiency of the axial compressor calculated from the history data using a fuzzy cluster **model**. This paper explains the main principles of how fuzzy cluster model can be built for performance reference value calculation. This method can be used for many types of compressors and applications where reference data is not otherwise available provided that sufficient amount of history data is available.

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The on-line performance system was developed and installed to one gas compressor unit. The operator interface consists of series of graphic displays presenting the current operating conditions and the reference values of a compressor unit. The validity of the performance calculations was evaluated by **third party** performance test. The percentual deviations were small. With the help of the performance monitoring system the performance degradation and fouling of the compressor unit can be evaluated and monitored.

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# GAS COMPRESSOR UNIT PERFORMANCE MONITORING USING FUZZY CLUSTERING

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## 1. Introduction

This paper has been prepared in co-operation between Gasum Oy and Metso Automation Ltd.

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Gasum Oy is a company based in Finland and is responsible for importing natural gas, maintaining and extending the natural gas pipeline in Finland and for marketing and selling natural gas to wholesale customers such as industrial plants, energy companies and local distribution companies.

Gasum Group consists of Gasum Oy, the parent company, and its subsidiaries which are mainly related to the gas equipment sales and service, gas distribution network operations and construction, gas sales to customers like for small industrial plants and domestic use. Gasum Group's turnover in year 2004 was 611 million €, operating profit was 46 million €. Number of employees of Gasum Group in 2004 was 184.

The history of Gasum starts from year 1971 when the contract to supply natural gas to Finland was undersigned by the governments of Soviet Union and Finland. Neste Oy, a Finnish oil, gas and chemical industry company, was nominated to be the company taking care of the gas transmission network construction, operation and maintenance as well as the sales and marketing of natural gas. The first cubic meter of natural gas was imported to Finland in 1974, when the gas network was some hundreds of kilometres long. During the second energy crisis in early 1980s the gas consumption was declining due high gas price caused by linkages to oil price. Nevertheless, the management of the company decided to extent the gas network in the southern part of Finland. The construction work was ready in 1985, and utilisation of gas started to increase steadily. Some additional branch lines were added to the gas transmission network later on and currently the gas transmission network covers about 1100 km of pipeline and around 200 gas delivery points. Currently, gas represents 11 % of primary energy consumption in Finland.

In 1994 Neste Oy natural gas and related assets were transferred to a founded company, Gasum Oy, which was owned by Neste Oy (75%) and OAO Gazprom (25%). As a consequence of the merger between Imatran Voima Oy, a Finnish electricity company, and Neste Oy to form Fortum Oy, major part of Gasum was sold in 1999 in order to fulfill the EU requirements concerning the monopolistic position in energy markets. The ownership structure currently is:

|                                 |     |
|---------------------------------|-----|
| Fortum Oy                       | 31% |
| OAO Gazprom                     | 25% |
| Finnish state                   | 24% |
| Ruhrgas Energie Beteiligungs AG | 20% |

Metso Automation Ltd is a fully owned subsidiary of Metso Corporation. Our mission is to continuously create value by matching our inventories of process automation knowledge and experience to your business vision. We deliver results that make a positive contribution to the success of your operations. Our automation, information management, flow control products and solutions ensure your processes make the right quality product at high efficiencies and lowest possible cost - all the time. These objectives are embodied in our commitments to Results and Intelligent Reliability

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Metso Automation operates worldwide and has sales and customer support units in 36 countries in Europe, North and South America, Asia and Australia, and Africa. In 2004, Metso Automation's net sales were EUR 535 million. The number of employees totals approximately 3,300.

Metso is a global engineering and technology corporation with 2004 net sales of approximately EUR 4 billion. Its 22 000 employees in more than 50 countries serve customers in the pulp and paper industry, rock and minerals processing, the energy industry and selected other industries.

In the beginning of the year 2001, Metso Corporation's automation and control technology business area was renamed Metso Automation. Formerly the name of the company was Neles Automation which was formed in 1999 by merging two companies, Neles Controls and Valmet Automation. Both companies have advanced across a multi-phased history in attaining an outstanding worldwide position as process instrumentation, automation and flow control suppliers.

## 2. Background

Process performance monitoring is an essential tool for predictive maintenance and efficient operation. Proper use of process performance indicators can help maintenance management to make right decisions on necessity and timing of preventive or corrective maintenance activities or even major overhauls. Process performance monitoring gives plant management also tools for evaluating effect of different operating schemes and to improve the energy efficiency of the units.

Above applies to gas compressor units that are used for gas pumping purposes in gas transmission system. Therefore Gasum Oy decided to develop an on-line performance monitoring system for gas compressor unit on-line performance monitoring purposes together with Metso Automation Ltd. In order to develop the system, a joint effort was launched. As one part of the project, a Master's thesis for Tampere University of Technology, Finland was prepared. In this thesis, full details of the on-line performance monitoring system are presented. (Salmela, 2005)

In this paper, main interest is in the axial compressor of a gas turbine, which drives the compressor unit. Description of compressor operating map in next paragraph and later, the utilisation of fuzzy clustering, apply in principle to radial gas compressor as well as to axial air compressor of the gas turbine. In the on-line performance monitoring system development phase fuzzy clustering was used in determination of reference values for gas turbine's axial compressor as well as for radial gas compressor. The emphasis in this paper is in the axial compressor.

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## 3. Compressor efficiency

### 3.1 Compressor operating map

Typically radial gas compressors are used in natural gas transmission pipelines. The characteristics of a gas compressor depend on design and can be tailor-made to each required configuration. These characteristics are normally presented as an operating map of the compressor unit. The operating map displays the performance of the compressor unit in pressure ratio versus mass flow and rotating speed. An example of the operating map is displayed in figure 3. In the operating map, constant speed curves are displayed. The left ends of speed curves have been connected with a line called surge limit. The right ends of speed curves are called stonewall limit. (Cohen et al., 1996)

From the operating curves it is clearly visible that the operating area between the surge limit and stonewall is relatively large. Operating area is decreasing the higher the pressure ratio because the surge starts with higher mass flows than at lower pressure ratios. (Sayers, 1990) In the case of natural gas compressor, the right limit is seldom determined by choking of the compressor at stonewall limit. (ANON.)

Efficiency of the compressor at constant speed varies in relation to the mass flow. From the operating map, a set of efficiency curves can be constructed as displayed in the figure 1. Nevertheless, the maximum efficiency at each rotating speed is located about at the same rotating speed. It is often the

case, that the operating map displays constant efficiency curves. Maximum efficiency curve is often close to the surge limit, as displayed in the figure 1 on the left side. (Cohen et al., 1996)

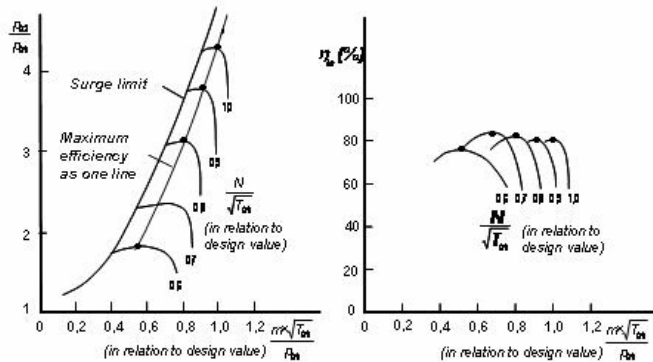


Figure 1, typical compressor operating map

### 3.2 Compressor operating map normalization

The performance of a compressor can be visualized by operating maps where delivery pressure or pressure ratio is plotted against mass flow at different fixed rotational speeds. These characteristics, however, are dependent on other variables such as inlet conditions of pressure and temperature and physical properties of the working fluid. Any attempt to allow for full variations of all these quantities over the working range would involve an excessive number of experiments and make a concise presentation of the results impossible. Much of this complication may be eliminated using the technique of dimensional analysis, by which the variables involved may be combined to form a smaller and more manageable number of dimensionless groups. (Cohen et al., 1996)

In the case of this paper, the operating parameters of the gas turbine's axial compressor were normalized using a table where polytropic efficiency is function of pressure ratio ( $\rho$ ) and  $\Omega$ .  $\Omega$  is temperature normalized rotational speed. This creates an invariant system, where the changes in inlet conditions are eliminated and thus the characteristics of a compressor are comparable at each operating condition. This normalization system is presented in the Nuovo Pignone customer information letter NIC96.07.

### 3.3 Performance degradation

Compressor performance degradation can be divided in three different types. The first one is recoverable by compressor cleaning and washing. Next degradation type cannot be recovered, while it represents degradation due to wear of the parts. Third type of degradation is permanent which cannot be recovered by changing any parts. (Peltonen, 1997)

Even though a compressor is equipped with a proper filter, in normal operation, dirt, dust and small particles are conveyed into a compressor with the working fluid flow. This causes contamination of flow surfaces, changes blade profiles and causes changes into flow patterns. Due to the contamination of flow surfaces inlet flow to the compressor is reduced and performance of different parts of the compressor is reduced differently. This will cause the overall efficiency reduction of the compressor. (Peltonen, 1997)

Efficiency can be improved by washing and cleaning the compressor. This washing and cleaning can be done as an on-line washing, when the compressor is in operation or as an off-line washing, when

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the compressor is stopped for the cleaning work. These methods are widely used in gas turbines' axial compressor cleaning. Even the washing is done regularly, a small amount of dirt still remains in flow surfaces and thus degradation cannot be completely recovered. In addition to that, **cleaning cannot repair** erosion and corrosion of flow surfaces. (Peltonen, 1997)

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In a major overhaul of the compressor it is completely disassembled, components are thoroughly cleaned, faulty components are replaced and flow surfaces are recoated and worn seals are replaced. Major overhaul will return the performance of the compressor as close to the performance of a new compressor as possible. In theory, the performance of the overhauled compressor should be the same as the performance of a new compressor, but in reality this is not possible. In the overhauled compressor there will always remain some seal leakages, uneven flow surfaces, alignment errors etc. that will cause some aerodynamic performance reduction. This performance reduction is nevertheless small. (Peltonen, 1997)

It is essential to detect degradation before corrective action can be started (Diakunchak, 1992). Real time condition monitoring is an important part of modern and efficient management of industrial flow machines (Mathioudakis et al. 2001). Compressor performance can be estimated by regularly following certain parameters of the compressor, for example efficiency or the required shaft power of the compressor. In order to reliably monitor performance, condition monitoring system **has to** produce a reference value against which the real operating value can be compared. Usually the reference value is selected so that it represents the reference value of a new compressor. (Diakunchak, 1992)

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Operating conditions of a compressor can vary significantly and thus the reference value cannot be a single value but a set of values or a normalized function.

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## 4. Development of the on-line performance monitoring system

### 4.1 Targets

The target of Gasum was to develop an 'easy-to-use' system as a part of the existing compressor stations' control and information system that utilizes existing field instrumentation, data collection and storage systems. Because the compressor units are remotely operated and monitored without any particular personnel monitoring the performance level, the target was to integrate into the existing control system some key performance indicators.

In addition to the on-line performance monitoring system, an off-line version was needed. The target of this off-line version was to provide a tool to the operators in order to determine the best possible compressor unit to be operated in each operating condition. Operator would give the desired gas compressor pressure ratio and gas flow as an input and receives the required fuel consumption of each compressor unit and if the required condition is out of compressor operating range. This fuel consumption information can be used as a basis for selection of unit to be operated

These starting points set the target to develop a robust, simple and low-cost performance monitoring system for gas compressor unit performance monitoring.

### 4.2 Reference data

For most processes performance indicators cannot be interpreted without a reference i.e. baseline data. This reference is a model of expected performance at the given operating conditions. An example of a typical model is a set of performance curves provided by a gas turbine or compressor manufacturer. An alternative way of providing a reference for performance indicators is looking at past performance of the process. This is actually only possibility in some cases, where manufacturer is not willing to provide performance curves. With this method, interest is on changes of the performance indicator, not necessarily

the absolute value of the indicator. Looking at past performance, the challenge is to find situations where external process conditions were similar enough for any comparison to make sense.

During the development of the on-line performance system for Gasum there was no manufacturer's performance curve available for the gas turbine's axial compressor and therefore it was decided to use the past performance data for reference calculations. This data was easily available in the information system as hourly average values. Needed and also available parameters were:

- air inlet temperature
  - air inlet pressure
  - discharge pressure
  - discharge temperature
  - rotational speed
- of the axial compressor.

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It was noted already in the data collection phase that some parameters, which were not available, were affecting the performance of the axial compressor and also gas turbine's overall efficiency calculations. These parameters were the position of inlet guide vanes, opening of the axial compressor blow off valves, inlet air humidity and pressure. The error caused by inlet air humidity and pressure was omitted from axial compressor reference value and actual performance calculations due to its relatively low impact, but it was included in the overall gas turbine performance calculations. The inlet guide vane position is changing and axial compressor blow off valves are open only when the compressor unit is in transient condition or at very low load. Therefore the data from that time, when inlet guide vanes were not in fully open position or axial compressor blow off valves were not closed, were also omitted from reference value calculations. Respectively, the actual performance calculation of axial compressor is stopped, when inlet guide vanes are not in fully open position or axial compressor blow off valves were not closed. Gas turbine overall performance calculation is in operation despite of that, because it utilises heat balance calculation and thus is not affected by these parameters.

Above listed parameters were retrieved from the information system, the sample included operational data from December 2003 to October 2004. The data was available directly in MS Excel software for further processing. So, a significant amount of data was available for reference value creation. A fuzzy clustering method was developed for reference creation. [Methodology was inspired by ground braking framework research on utilization of fuzzy methodology on performance improvement and optimization \(Joronen, 2005\)](#)

### 4.3 Fuzzy clustering

Fuzzy clustering can be utilized to automatically group, or cluster, similar instances of process conditions together and to find past performance under those process conditions. Fuzzy cluster model can then give reference value, or expected performance value, at current process conditions. Also other information on expected performance can be incorporated in the model. This is particularly useful when the process has not run in all relevant operation points during its recorded history.

[Data for constructing the performance reference model](#) was collected in the existing information management system. One hour averages were calculated from the raw data. These values were normalized for different operating conditions by calculating pressure ratio ( $\rho$ ) and temperature normalized rotation speed ( $\Omega$ ) in order to allow comparability. These normalized values were used for reference modeling. Values were originally grouped into two-dimensional clusters by triangular fuzzy membership functions. This ensured that each data point had equal weight in calculation of average values that were used to represent the data cluster. When this model is used to calculate expected performance, performance values are interpolated between centers of the clusters.

[However, during the development project, it was noted that this original approach has a minor problem with clusters that have data points only on one side of the cluster. For this reason, fuzzification](#)

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was given up in the forced clustering phase. Rho and Omega data were divided in ten (crisp) groups and these two dimensions then created the model, which has 100 classes. Each data point influences the value of one class. The class is represented by a value, which is calculated as arithmetic average of performance indicator data belonging into this class. In addition to the class value, value's location in the cell is calculated based on the performance indicator data. This location in reference to orthogonal coordinate system is calculated by weighed average of data points' coordinates (center of gravity). The result is a map representing the complete set of data. The values between the calculated data points can be obtained using interpolation (average of values of four surrounding classes, weighed with inverse of geometric distance between a data point and classes' centers of gravity). The areas outside the available data are extrapolated in order to allow interpolation also in the edges. This method moves fuzzification function into data mapping phase and improves model fidelity by retaining richer information on the original modeling data. Figure 2 displays an example of performance reference surface generated by the model.

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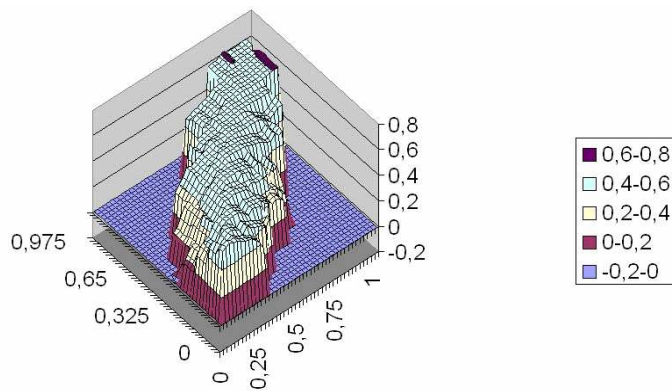


Figure 2, Performance reference surface

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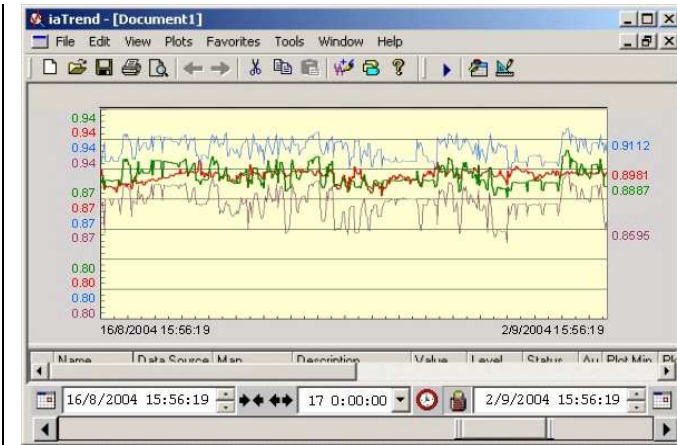
#### 4.4 Model's accuracy

Capability of the model to represent the sample data can be estimated by calculating a value for each performance indicator originally calculated from the process data sample. The difference (RMSE, root mean square error) between the calculated value by the model and real value are classified the same way as the original set of data to ten classes. Thus an average error for each class can be presented that also indicates the accuracy of the model. If the performance indicator calculated value from real process data differs from the model's calculated value by more than twice the average error during a determined time period (for example one hour), the performance is considered changed. In figure 3, the root mean square errors in each class of the model are displayed and figure 4 shows a practical visualization of calculated performance versus reference performance and 2-sigma confidence level of the reference value.

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| 0,7 % | 0,9 % | 0,9 % |       |       |       |       |       |       |       |
|       | 1,0 % | 0,8 % | 0,9 % |       |       |       |       |       |       |
|       |       | 1,4 % | 0,7 % | 0,8 % |       |       |       |       |       |
|       | 1,4 % | 1,7 % | 1,7 % | 0,8 % |       |       |       |       |       |
|       |       | 1,3 % | 1,6 % | 1,6 % |       |       |       |       |       |
|       |       | 1,3 % | 1,3 % | 1,3 % | 1,1 % | 0,6 % |       |       |       |
|       |       |       | 1,8 % | 1,3 % | 0,9 % | 1,1 % | 0,6 % | 0,5 % |       |
|       |       |       |       | 1,2 % | 0,8 % | 0,9 % | 0,8 % | 0,6 % | 0,6 % |
|       |       |       |       |       |       | 0,7 % | 0,7 % |       |       |

Figure 3, RMSE values of the data map.



Reference performance + 2-sigma  
 Actual performance  
 Reference performance  
 Reference performance - 2-sigma

Figure 4, Actual performance, Reference and 2-sigma confidence limits in trend display

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## 5. Results

This on-line performance monitoring system utilizing fuzzy clustering during development phase was installed into one compressor unit in winter 2005. The system was in operation for several months and the evaluation of results could be done. The results seems to be satisfactory: the system is simple to use, uses existing instrumentation and information system, investment costs were low and the performance indicators are relatively precise. The man-machine-interface is presented in figure 5.

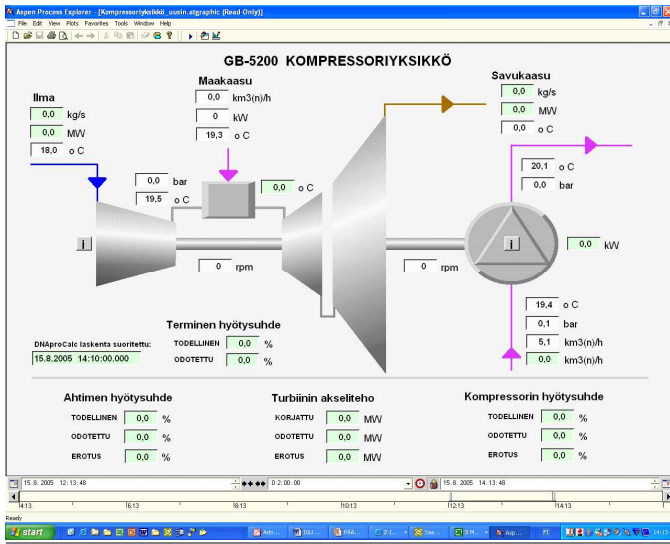


Figure 5, Man-machine-interface of the on-line performance monitoring system

A performance test was organized in order to compare the results of on-line performance monitoring system to results calculated by a third party performance test. This comparison indicated, that the relative difference in calculated efficiency was 1,5 % for the gas compressor and 5 % for the gas turbine. This difference was mainly caused by calibration errors and after taking them into account, the difference was reduced significantly. As noted in the beginning of this paper, the target was not to create an absolutely accurate on-line performance monitoring system but a system that can be used to monitor changes in the performance and so trigger corrective maintenance actions. This achieved accuracy was thus unexpectedly high and can be considered very satisfactory for the intended purposes.

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As noted, during the test period the system helped to identify some instrumentation faults and thus assisted in determining maintenance activities and removing control system related operational limitations. Gasum has plans to enlarge the system to cover further four units in 2006 after sufficient amount of data has been collected from these compressor units.

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## 6. Conclusions

It is relatively easy and simple to build a reference model of a gas compressor unit for performance monitoring purposes even no reference data is available from the manufacturer. This modeling can be done using fuzzy clustering method developed in this project and the actual modeling can be largely automated so that it does not require deep know-how of the statistical methods used. It is essential to obtain sufficient amount of process history data from sufficiently wide operating regime.

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This model was built to one Nuovo Pignone PGT10DLE gas turbine and PCL603 gas compressor in 2005 and has been in operation for one winter operating season. The results are promising and with the system, operating and maintenance people obtain information on-line about the current performance of the complete compressor unit and individual parts of it compared to the reference values.

## References

1. ANON. Centrifugal Compressors. Firenze, Italia: Nuovo Pignone. Training Center. [221 p.] **Met opmaak:** Fins

2. Cohen, H., Rogers, G.F.C., Saravanamuttoo, H. I. H. 1996. Gas turbine theory. 4.e. Essex, England: Longman Group Limited. [442 p.]

3. Diakunchak, I. S. 1992. Performance Deterioration in Industrial gas Turbines. Journal of Engineering for Gas Turbines and Power. Vol. 114. [ps. 161-168]

4. [Joronen, T. 2005. Framework for Process Performance Improvements by Fuzzy Control and Optimization, Doctoral Thesis, Tampere, Finland. Tampere University of Technology.](#)

5. Mathioudakis, K., Stamatis, A., Tsalavoutas, A., Aretakis, N. 2001. Performance analysis of industrial gas turbines for engine condition monitoring. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy. Vol. 215(2), [ps. 173-184] **Verwijderd:** 4

6. Peltonen, A. 1997. Gas Turbine Maintenance Management with On-line Gas Path Analysis. Thesis. Tampere, Finland. [Tampere University of Technology](#). [86 s.] **Verwijderd:** 5

**Verwijderd:** Tampere Technical University

7. Salmela M. 2005. Development of an Online Performance Monitoring System for Natural Gas Compressor. Thesis. Tampere, Finland. Tampere Technical University. [80 p.] **Verwijderd:** 6

8. Sayers, A. T. 1990. Hydraulic and Compressible Flow Turbomachines. London, UK: McGraw-Hill book Company (UK) Limited. [301 p.] **Verwijderd:** 7

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