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Condition monitoring and diagnostics of machines — Approaches for performance diagnosis

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National foreword

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the WTO principles in the Technical Barriers to Trade (TBT), see the following URL: Foreword — Supplementary information.

The committee responsible for this document is ISO/TC 108, *Mechanical vibration, shock and condition monitoring*, Subcommittee SC 5, *Condition monitoring and diagnostics of machines*.

Introduction

Challenged with high energy costs, emission reduction demands, and increasing flexibility demands, ensuring and verifying maximum efficiency of machines and systems has become a constant struggle for owners and operators.

Machines, groups of machines or industrial installations (equipment) fulfil their tasks by employing energy conversion or energy transportation processes. The efficiency of these energy conversion and energy transportation processes is the performance of the equipment or related processes. Good performance means high efficiency and low losses. If the energy conversion process includes a thermodynamic process, especially a thermodynamic cycle process, performance monitoring can become very complex.

Performance monitoring and diagnostics systems are increasingly implemented for this purpose. These are modern information systems that monitor the processes of machines, groups of machines, or complete industrial installation in order to detect and localize opportunities to improve their efficiency respective performance.

The benefits of performance monitoring and diagnostics lie in the provision of information (e.g. measured descriptors and expected descriptors) regarding the current performance status of the equipment. This information is the basis to avoid non-optimal operating states, degradation processes, and to ensure early detection and quantification of deterioration processes (e.g. erosion, corrosion).

Performance monitoring is often used in addition to condition monitoring.

Targets of performance monitoring and diagnostics are

— enhanced quality of energy conversion by achieving optimized operation,

— emission reduction,

— quantifying deterioration,

— recognizing faulty instrumentation,

— detecting defective equipment,

— enhanced availability of machines,

— increasing efficiency, thereby reducing energy costs and costs for emissions, and

— improvement in internal reporting and communication by increased transparency and calculation of well-defined descriptors.

Results of performance monitoring and diagnostics are addressed to

— operators to change the operating regime in case of identified not optimal operation, and

— maintenance staff to repair or modify the machine or equipment in order to eliminate identified faults/deterioration.

Condition monitoring and diagnostics of machines — Approaches for performance diagnosis

1 Scope

This International Standard provides an introduction on how to apply performance monitoring and diagnostics for machines, groups of machines, up to complete industrial installation (equipment) typically covering the whole lifetime of the machines.

This International Standard is intended to

— introduce the terminology specifically related to performance monitoring and diagnostics of machines,

— describe the types of performance monitoring and diagnostics procedures and their merits,

— provide guidance on installation of performance monitoring and diagnostics systems,

— outline methods and requirements for carrying out performance monitoring and diagnostics of machines, and

— provide information on data interpretation, and assessment criteria and reporting requirements.

This International Standard includes testing procedures for determining the accuracy of performance monitoring and diagnostics systems and procedures (including providing inputs for benchmarking the performance of equipment).

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 13372, *Condition monitoring and diagnostics of machines — Vocabulary*

ISO 13379-1, *Condition monitoring and diagnostics of machines — Data interpretation and diagnostics techniques — Part 1: General guidelines*

ISO 17359, *Condition monitoring and diagnostics of machines — General guidelines*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 13372, ISO 13379-1, ISO 17359, and the following apply.

3.1
performance
behaviour, characteristics and efficiency of a technological process, running in a machine derived by measurement and calculation of one or more parameters, for example, power, flow, efficiency or speed, which singly or together provide the necessary information

[SOURCE: ISO 13372:2012, 2.3]

Note 1 to entry: Performance is used to qualify energy conversion processes with mostly thermodynamic process parts included.

Note 2 to entry: According to ISO 13372 machines, group of machines and complete industrial installations are referred to as equipment.

3.2
thermodynamic process
energy conversion process where thermal energy is involved as a major energy form

3.3
steady state
operating condition whereby the value of the described signal does not vary significantly with time

Note 1 to entry: A process is regarded as steady-state when characteristic parameters are steady-state.

3.4
descriptor
feature
data item derived from raw or processed parameters or external observation

[SOURCE: ISO 13372:2012, 6.2]

3.5
measured descriptor
signal obtained directly from the monitored equipment as measured value or processed directly from measured values, which is relevant for performance

3.6
expected descriptor
corresponding value to a measured descriptor that is obtained from a model, where the model describes the expected performance of the equipment

3.7
performance factor
ratio between actual value and expected value of efficiency

Note 1 to entry: A performance factor greater than 100 % means “better than target”, less than 100 % is deterioration.

Note 2 to entry: It is expressed as a percentage (%).

4 Types of performance monitoring and diagnostics

4.1 Basic concepts

Performance monitoring typically includes a comparison between measured descriptors (describing the performance of a machine, for example, power, flow, efficiency) against the expected descriptors.

The assessment of the performance by comparison requires identical operating conditions, such as speed, load, or temperature. Therefore, reference operating conditions are needed. With respect to the objective of the performance monitoring, different concepts are applicable:

a) Performance monitoring at actual measurement conditions – the operating conditions during measurement are used as reference and the expected descriptors are converted into values at these conditions. This concept is preferred, if for example, information about actual losses due to degradation under the present operating conditions is demanded.

b) Defined operating conditions are used as reference for performance monitoring. The measured descriptors gained at present operating conditions are converted into values at reference conditions. This method is preferred for trending purposes to eliminate the operating conditions influence.

NOTE Where correction to reference conditions is required, advice is given in the appropriate acceptance testing standard. A selection of International Standards relating to performance and acceptance testing is included in the Bibliography to ISO 17359.

4.2 Online performance monitoring

The basis of online performance monitoring is a model of the process running in a machine (e.g. thermodynamic process like Clausius-Rankine-Cycle or Joule Cycle).

Calculation results of the model are referred to as “expected” descriptors as they represent the theoretical or healthy status of the equipment for given operating conditions, i.e. without consideration of degradation, fouling, and faults. Here, the operating conditions are characterized by a small number of input parameters which are taken from measured values (in general, ambient conditions, fuel properties, speed, load, etc.).

The comparison of measured descriptors with expected descriptors allows monitoring of component performance, identification of abnormal performance situations, and analysis of component performance and abnormal operating conditions.

The monitoring of abnormal situations is followed by an analysis. This analysis is supported by the computation of key performance parameters (e.g. efficiencies and losses). Such parameters are derived from both corresponding measured descriptors and expected descriptors obtained with the model.

4.3 Offline performance analysis

Offline performance analysis is based on the same or a similar sophisticated model as online performance monitoring.

However, offline performance analysis allows controlled variation of the input parameters or the model characteristics.

This provides the basis for “what-happens-if” calculations, which are helpful for diagnostics of deviations between measured and expected descriptors from online performance monitoring.

4.4 Online performance monitoring with validation

In order to enhance data quality and to detect corrupt measurements, data validation according to VDI 2048-1 is recommended.

Using this method of data reconciliation, validated results provide a consistent set of measurements and the accuracy is enhanced overall. This allows better comparison of measured descriptors with expected descriptors.

The calculation process is strongly dependent on the availability of redundant or physically related measurements and the accuracy of the measured descriptors.

By building closed energy and mass balances, additional (not measured or not measurable) parameters can be calculated like heating surface properties that are not available without data reconciliation.

NOTE An inconsistent set of measurements can be detected by the validation process. Therefore, online performance monitoring with validation is helpful to enhance data quality and to detect suspect measurements.

5 Guidance on installation of performance monitoring and diagnostics systems

5.1 Preconditions

A general precondition of performance monitoring and diagnostics system is that the operating characteristics of the equipment to be monitored match the required function.

NOTE Errors arising from inadequate system design cannot be corrected by means of performance monitoring.

The following prerequisites are recommended for analysis of suitability:

— All machines of the equipment under consideration should run at manufacturer specified nominal conditions (characterized by, for example, flow, pressure, temperature, power).

— If a machine is operated in partial load or overload regions, at least these regions should belong to the allowable operating region specified by the manufacturer.

NOTE High efficiency of a machine is not identical with high efficiency of the equipment to which the machine belongs if, for example, the machine always runs in partial load.

5.2 Planning

Before performance monitoring and diagnostics are started, the following steps should be carried out:

— analyse operation of the machines and define output performance parameters (pairs of actual measured and expected descriptors);

— select input parameters to be used (see Annex A);

— define operation states foreseen for performance monitoring, including defining the steady-state condition for the monitored equipment;

— adjust the model for the monitored equipment;

— test the performance monitoring.

5.3 Operation analysis of equipment and definition of output performance parameters

The objective of the operation analysis of the equipment is the selection of descriptors describing the performance of the equipment and its components. The following items should be taken into account:

— determination of the required function of the equipment;

— evaluation of the required function of the equipment concerning behaviour, characteristics, and efficiency to be essential and representative for performance;

— comparison of equipment's design with the required function in order to analyse the capability to meet the required function;

— evaluation of the nominal operation parameters;

— analysis of procedures and constraints influencing the operational behaviour of the equipment;

— determination of descriptors describing the performance of the equipment (see Annex B);

— equipment break down into main components representing the main functions of the equipment;

— analysis of the interaction of the components.

The result of the analysis should be a set of descriptors (output performance parameters), which can be measured directly or derived from measured values.

5.4 Definition of operation states

5.4.1 General

It is recommended that performance monitoring and diagnostics be carried out for standard operation states of the equipment, which are defined as follows:

— steady-state operation;

— equipment is in operation with load or power above a specified minimum load or power;

— main operation characteristics (e.g. speed, valve positions, bypasses) are within specified ranges.

The result of this operation analysis is a list of operation states with their specification.

NOTE The performance monitoring can be limited to some specified operation states. Other operation states are defined as non-standard operation states and will not be considered.

5.4.2 Steady state

Models used for performance monitoring are based on assumptions concerning the operation states of the machines. Usually, steady state is required. This implies stabilization of characteristic performance parameters (descriptors).

The following method is an example for a robust estimation of steady state (see Figure 1).

The steady-state conditions are defined by

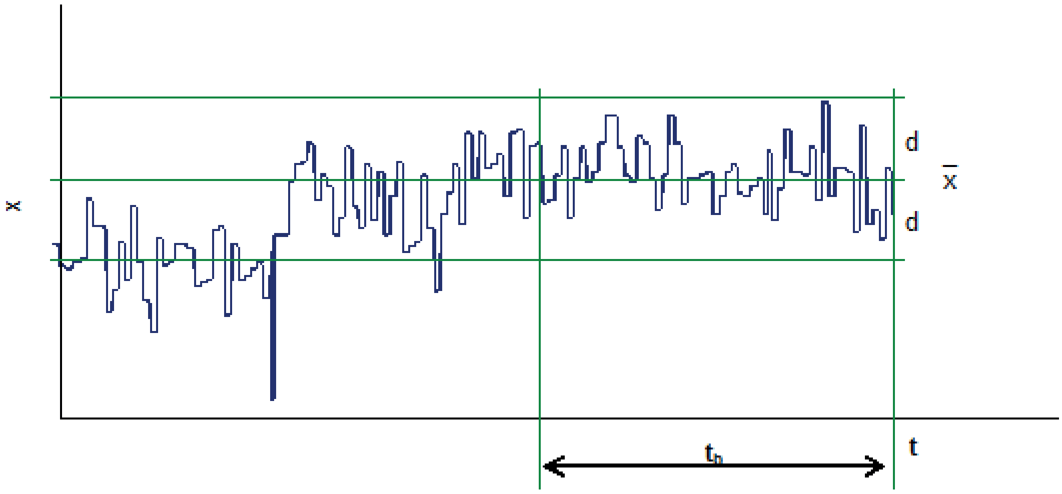
— selecting descriptors of the machine, suitable to describe operation states and available as measured signals,

— defining the allowable fluctuation range $2d$ for each descriptor (e.g. peak-peak-value of the descriptor), and

— specifying the length of a moving time window t_b:

— calculating the mean value $\bar{x}$ over the time $t - t_b$ to t, counting back from the current time t, the result is the arithmetic average over the length of the moving time window;

— checking whether the signal $\boldsymbol{x}$ during time $t - t_b$ to t is within the fluctuation range between $\bar{x} - d$ and $\bar{x} + d$ interval, if it is inside, then it is “steady state”.



Key

x	signal value
t	time
t_b	length of moving time window
2d	fluctuation range (*d* + *d*)
$\overline{x}$	mean value

Figure 1 — Estimation of steady-state for signal *x* (the signal shown is steady-state at time, *t*, but was not earlier)

The fluctuation range, 2*d*, and the length of the moving time window, t_b, shall be adjusted according the requirements of the model used and the monitored equipment.

EXAMPLE Parameters of a steam turbine for distinguishing steady-state conditions from non-steady-state conditions can be power and main steam mass flow. Typical fluctuation ranges *2d* for these parameters are 5 % of the values at nominal power and a length of the moving time window, t_b, of e.g. 10 min.

5.4.3 Nominal state

The nominal state of the equipment is the design case. Usually, the nominal state is equivalent to the full-load case.

In practice, the equipment is operated in nominal state during the acceptance test of this equipment.

5.4.4 Partial load states

One or more partial load states should be defined. A new partial load state should be defined if the measured descriptors differ significantly from the nominal state or other partial load states.

The model should be able to provide expected descriptors for all defined partial load states.

5.5 Adjusting the model

The model of the equipment should be compiled from model components. Typical components are

— gas turbines,

— steam turbines,

— generators,

— motors,

— heat exchangers,

— steam generators,

— condensers,

— pumps,

— valves, and

— pipes.

It should be possible to calculate performance parameters for each model component from its input parameters. The input parameters are measured signals.

The model itself consists of

— closed formulas, or

— mathematical equation set, which needs to be solved, or

— a set of characteristic curves describing the process taking place in a component.

The deviations between measured and expected descriptors in the adjusted model should be less than the promised accuracy of the model.

This should be achieved by varying parameters within the mathematical equations or the characteristic curves. The adjustments should be done for all specified operation conditions.

5.6 Testing the performance monitoring

The test of performance monitoring should contain the following items:

— for each component of the equipment, a model is assigned;

— the model of the equipment comprises the models of all components;

— all required input parameters from the models used are available;

— all required output parameters of the models are available from the equipment for comparison or can be derived;

— the calculated steady-state condition is correct;

— the measured values are checked for plausibility;

— the model of the equipment provides correct results for input test data; at a minimum, the test data cover the nominal operation of the equipment;

— the adjustment of the model is documented and tested for each defined partial load state;

— a cycle time for performance monitoring is defined;

— the performance monitoring detects the actual condition of the equipment (nominal state, partial load states) and shows this information;

— the documentation concerning the performance monitoring is complete and available.

6 Methods and requirements for carrying out performance monitoring and diagnostics of machines

6.1 Methodology

The performance monitoring and diagnostics should run continuously or periodically (every week, for example). In general, the input data used should be standard process data of the equipment.

It is recommended that the performance monitoring and diagnostics are based on mean values over specified time intervals and steady-state conditions. This reduces measured value signal noise.

The model is fed with a small number of input parameters characterizing the operating conditions, which are taken from measured process values (in general, ambient conditions, fuel properties, power or load level of the equipment, etc.).

The results of the model (the expected descriptors, representing the theoretical status of the equipment for the given operating conditions) are compared with measured descriptors. Deviations between measured and related expected descriptors allow detection of abnormal performance and analysis of the root cause.

The accuracy of the comparison depends on the quality of the measured signals, their availability, and the accuracy of the equipment model.

To ensure accurate expected descriptor calculation results, the model should be adjusted based on actual equipment data (see 5.5).

6.2 Plausibility check

It is recommended to carry out a plausibility check of the input data before running the model. This check should involve comparison to predefined minimum and maximum levels for each input signal. If the data are not within the predefined range, the calculation should not be started or a default or substitute value should be used instead, depending on the signal's relevance for the process of the equipment.

6.3 Cycle times and averaging

The cycle time defines the time interval for how frequently calculations for performance monitoring are initiated. Performance monitoring is not safety related nor immediately critical to equipment operation. Therefore, cycle times of 1 min to 15 min are recommended.

For each time interval fulfilling the steady-state condition, the input data from the equipment's process control system should be averaged before the calculation process is initiated.

6.4 Implemented calculations and input parameters

Figure 2 shows the schema of calculation steps for performance monitoring.

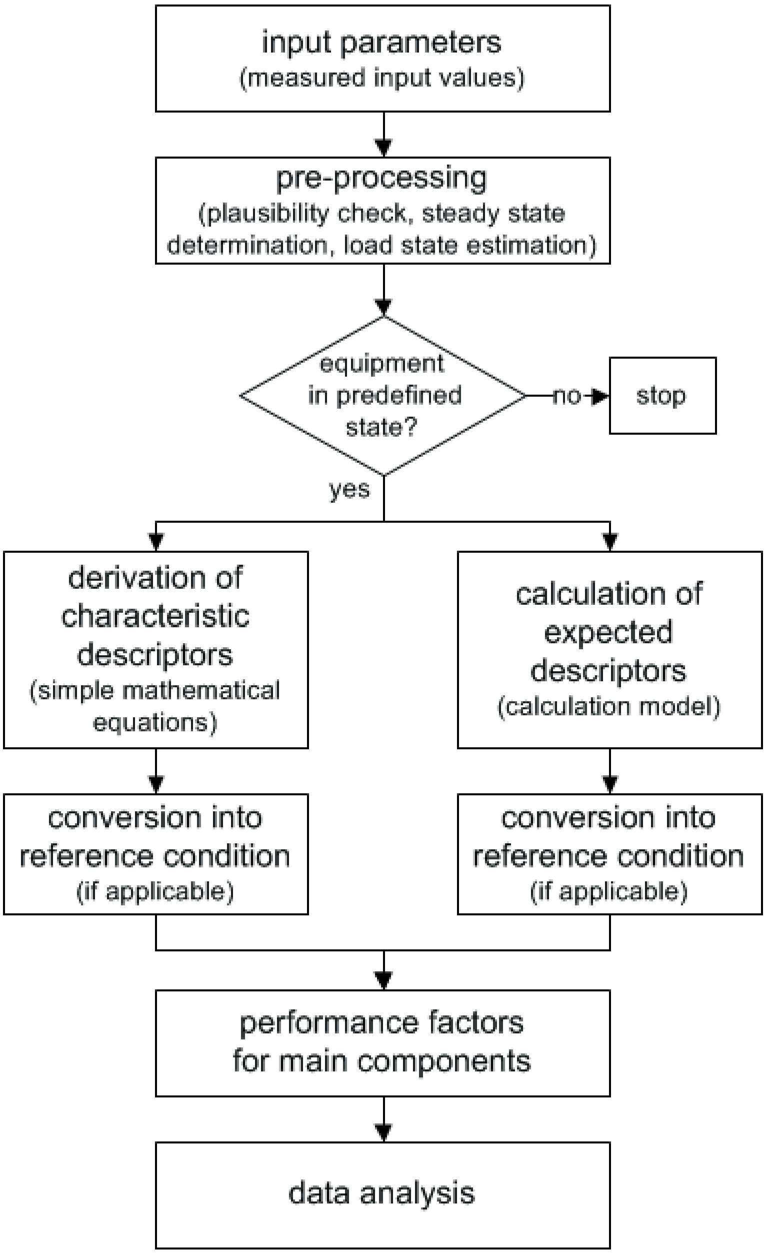


Figure 2 — Schema of calculation steps for performance monitoring

Input parameters are measured directly from the equipment every cycle time as a whole set of input values.

The input parameters pass a pre-processing, which contains

— plausibility check,

— determination of steady state, and

— estimation whether the equipment is in nominal state or in a defined partial load state or in neither.

The pre-processing is followed by the input data processing, which is split into two branches (only for nominal state and defined partial load states):

a) The measured descriptors for performance monitoring (see 5.3) are derived, by simple mathematical equations, directly from the measured input values.

b) The expected descriptors, related to the measured descriptors from branch a), will be calculated by the model using the set of input values.

NOTE For the calculation of expected descriptors, only a few input values are used, which characterize the operational condition, for example, ambient conditions, power or load of the equipment, fuel heat rate.

The determination of the measured descriptors and of the expected descriptors may contain the conversion into descriptors at reference operational conditions. Alternatively, this conversion step should be added as a separate stage.

The final step is the comparison of the measured descriptors with the expected descriptors.

It is recommended to introduce a performance factor, for example, the ratio between actual efficiency and expected efficiency, to evaluate losses.

6.5 Validation

In order to enhance data quality and detection of corrupt measurements, data validation according to VDI 2048-1 is recommended. This method of data reconciliation provides validated results for a set of measurements. This allows the comparison of these validated results with the original measured signal readings and with expected descriptors.

The mathematical background of this method is described in detail in Reference [1]. The computational method is strongly influenced by the availability of redundant or related measurement sensors and the accuracy of the sensor readings. The set-up of the validation calculation for the present equipment is based upon the existing sensor equipment without additional implementation of sensors for better redundancy.

NOTE 1 The comparison between validated results and the original measured values for the same signal provides information about the quality of the measured signal, especially if the sensor is disturbed.

NOTE 2 If the measured values are of good quality, significant differences between validated results and original measured values suggest deviations in the process running in the equipment, for instance, leaks or valve malfunction.

7 Data interpretation and assessment criteria

Data interpretation of performance monitoring requires knowledge of the operating conditions and the conversion into reference conditions (see 4.1).

In general, the data interpretation should proceed from the whole equipment to the single component. A decrease of performance (decrease of measured descriptors describing the performance) indicates a malfunction or degradation of one or more components. A detailed performance analysis should be processed for each component: comparison between measured descriptors with expected descriptors.

NOTE It is good practice to list deviations between measured and expected descriptors together with the quantified losses or gains of power and efficiency caused by the deviation under consideration. A preferred presentation is to group the list into sections of main components. This overview is often referred to as “list of controllable losses”.

The selection of the reference operating conditions allows the following analyses:

a) actual measurement conditions are used as reference:

— determination of reserves at current operating conditions;

— assessment of whether equipment has the needed performance to fulfil its required function;

— identification of the component of the equipment with the weakest performance.

b) defined (fixed) operating conditions are used as reference:

— analysis of the trends of measured descriptors in order to evaluate degradation processes;

— detection of suddenly occurring deviations in the process running in the equipment;

— finding causes of deviation of the equipment performance.

Annex C shows an example of pump performance monitoring, where the actual measurement conditions are used as reference.

In Annex D, an example of gas turbine hydraulic clearance optimization is given, where fixed reference conditions are used for data interpretation.

Annex A
(informative)

Input parameters recommended for describing the operating conditions

Equipment components descriptor	As component of machine systems								As single machine		
	General equipment	Gas turbine	Steam turbine	Heat exchanger	Steam generator	Conden-ser	Valve	Pipe	Genera-tor	Motor	Pump
Ambient temperature		x								x	
Ambient pressure		x									
Ambient humidity		x									
Cooling water temperature			x			x					
Working medium temperature							x	x			x
Input pres-sure				x	x		x	x			x
Output pressure				x	x		x	x			x
Rotational frequency (speed)		x	x						x	x	x
Load			x						x	x	x
Fuel heat rate		x									
Mass flow (hot, cold)				x	x	x					
Inlet temperature (hot, cold)				x	x	x					

Annex B
(informative)

Measured and expected descriptors recommended for performance monitoring and diagnostics

Equipment components descriptor	As component of machine systems								As single machine		
	General equipment	Gas turbine	Steam turbine	Heat exchanger	Steam generator	Conden-ser	Valve	Pipe	Genera-tor	Motor	Pump
Gross power	x	x	x	x					x	x	x
Net power	x										
Gross efficiency	x	x	x		x				x	x	x
Net efficiency	x										
Isentropic efficiency		x	x								
Terminal temperature difference				x		x					

Annex C
(informative)

Example of pump performance monitoring

The goal of pump performance monitoring is the surveillance of characteristic pump parameters in order to ensure efficient operation. Typical descriptors are head, efficiency, and net positive suction head.

The measured descriptors are compared with expected descriptors derived from pump curves gained during the acceptance test of the pump.

Figure C.1 shows the performance monitoring results of a pump.

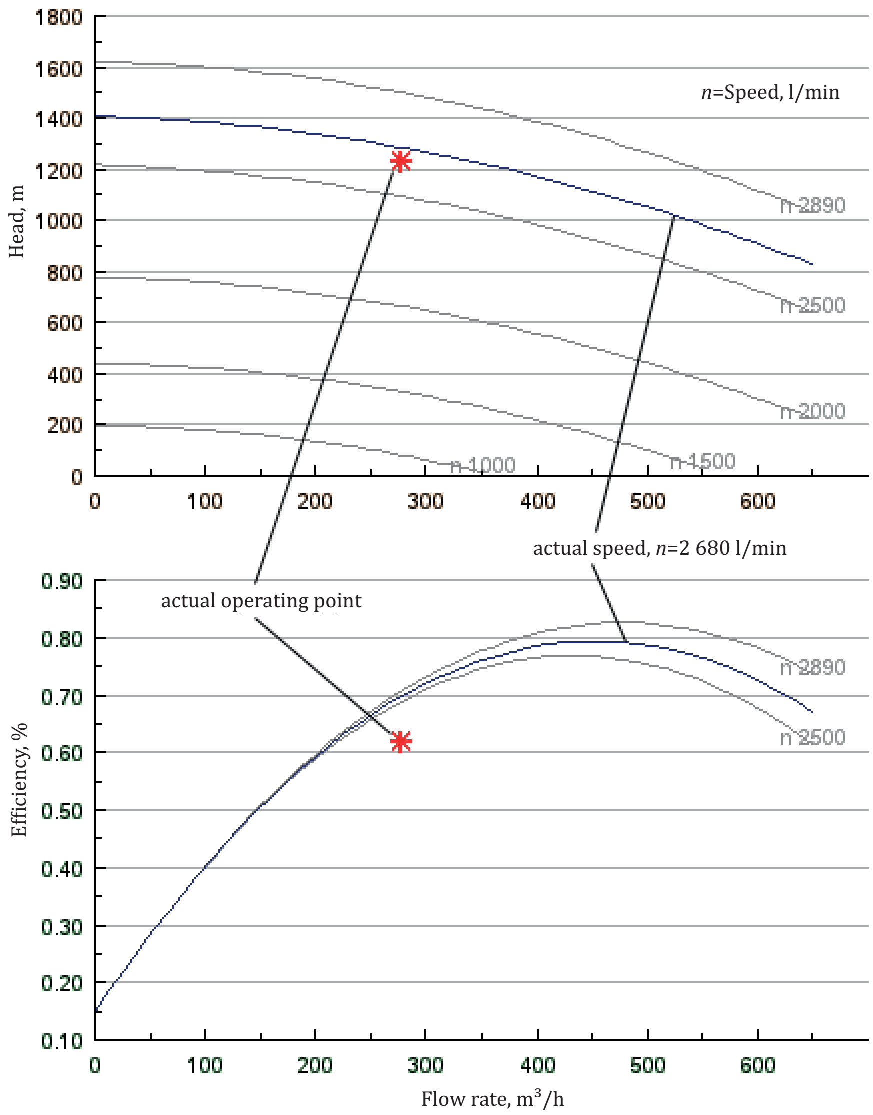


Figure C.1 — Example of pump curves used for performance monitoring

The model to determine expected descriptors of the pump consists of a set of pump curves for head and efficiency over the flow rate with rotational frequency (speed) as operational descriptor (drawn in light grey). For the actual measured rotational frequency (speed [n = 2 680 l/min]) the pump curves are processed by the model and highlighted in dark in Figure C.1. The other descriptors in the example are:

head (measured)	= 1 228 m
flow rate (measured)	= 277 m^3/h
electrical power (measured)	= 1 500 kW
rotational frequency (speed) (measured)	= 2 680 l/min
efficiency (measured)	= 62 %

The actual (measured) efficiency, η, of the pump is processed from measured values according to Formula (C.1):

$$\eta = \frac{P_\mathrm{h}}{P_\mathrm{el}} = \frac{Q\,H\,\rho\,g}{P_\mathrm{el}} \tag{C.1}$$

where:

- η is the efficiency;
- P_h is the pump output hydraulic power (kW);
- P_el is the pump input electrical power (kW);
- Q is the flow rate (m^3/h);
- H is the head (m);
- ρ is the density (kg/m^3);
- g is 9,81 m/s^2.

Unit relations or conversion should be taken into account, especially 1 h = 3 600 s and 1 000 kg · m^2/s^3 = l kW.

From the pump curves, the expected efficiency for this example (see Figure C.1) is 70 % at the measured rotational frequency (speed) of 2 680 l/min as reference.

For performance monitoring the introduction of a performance factor (given in %), η_p, as ratio between measured and expected efficiency is recommended.

$$\eta_\mathrm{p} = \frac{\eta_\mathrm{measured}}{\eta_\mathrm{expected}} \tag{C.2}$$

In the example of Figure C.1, the performance factor, η_p, is 89 %.

Annex D
(informative)

Example of gas turbine — Hydraulic clearance optimization

Gas turbines are equipped with hydraulic clearance optimization (HCO). HCO minimizes the gap between gas turbine blades and casing after warming up the gas turbine. During steady-state operation, HCO is generally in operation. The following example shows the impact on power plant performance of taking HCO out of operation manually.

In Figure D.1, the gross electrical power of a combined cycle power plant is depicted over a period of 4 h. The power is converted to reference conditions to eliminate the dependence on varying ambient conditions. Then, the converted power value is comparable to the constant power at reference conditions. If no issue occurs during operation, a horizontal line for converted power is expected.

At 23:30 h, power decreases significantly from 424,8 MW to 420,0 MW. For the period from 23:30 h to 0:00 h, no values are calculated, since the power plant is not in steady-state.

An analysis was carried out to determine the root cause for this effect. The power drop was caused by manually taking HCO out of operation.

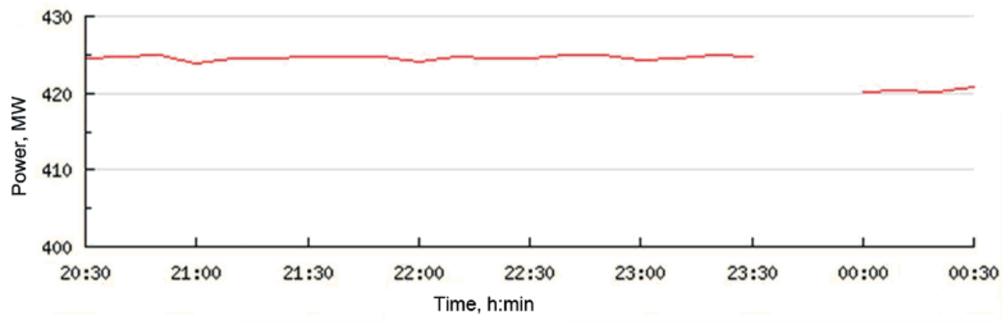


Figure D.1 — Gross electrical power converted to reference conditions

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[1] VDI 2048-1, *Uncertainties of measurement during acceptance tests on energy-conversion and power plants — Fundamentals*

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