Open Access Journal

Journal of Power Technologies 97 (2) (2017) 142–148

journal homepage:papers.itc.pw.edu.pl

The influence of measurement inaccuracies on the assessment of the state of gas turbines in diagnostic systems

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Abstract

The systems that monitor the performance of power generating units do so on the basis of measurements made during the operation of machines and devices. Every measurement inaccuracy influences the results of the performance assessment. The paper describes a comparison between the inaccuracies of the measurements taken in various sections of gas turbines and their influence on the calculations of chosen performance indices. The analysis is shown for a monitoring system that applies mass and energy balances of a gas turbine in the on-line mode.

Keywords: gas turbine, diagnostic, efficiency, measurements

1. Introduction

Monitoring and diagnostic systems in the power generation industry generally involve a two-step procedure to evaluate the performance (health state) of a machine. The first step involves taking the measurements themselves and the second is data processing. The number and positioning of sensors mounted on a machine may differ depending on the range of the monitoring. In this paper the monitoring under analysis relates to the efficiency of power generation.

Typically measurement errors exist and must be taken into account during the diagnostic procedure. Errors derive from various sources and the most common ones are described below.

The most natural is the uncertainty related to the deviations of the results of measurements from the true value [1]. The deviations may be either random due to limitations in the accuracy of the sensors or systematic when caused by some factor that influences the diagnostic observation of a machine's behavior. The influence of random deviations may be reduced when a measurement is repeated. Systematic errors may be reduced if care is taken to correctly calibrate the measurement equipment.

Other error types include non-representative location of a sensor. For example, a temperature probe in a highly turbulent flow through a relatively large cross-section may provide different results in various locations across the channel [6]. This can occur when measuring exhaust temperatures in gas turbines. The sensors are placed after the last stage of the turbine in a short but wide outlet section. The flow field in this area is turbulent, with streams of varying temperature mixing there [4]. The location of the temperature probe must be carefully chosen in order to show a value close to the average value of the gas temperature. Often several probes are inserted along the circumference of the

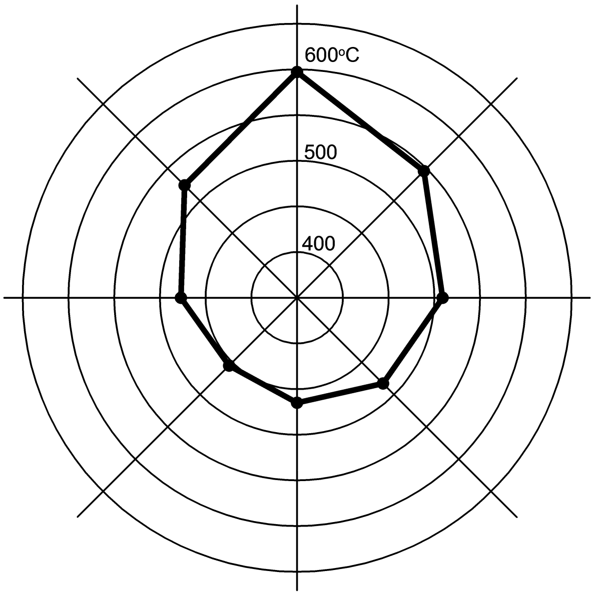

Figure 1: Measurement results of the exhaust gas outlet temperature

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outlet channel in order to validate the results [8]. An example of values from such measurement is shown in Fig. 1.

Further errors may arise in analysis of the transient operation. The changes in operation occur with inertia and any two measurements taken at the same time in two different locations in a machine may not reflect the transient process [2].

Any measurement error affects the subsequent data processing. It is then important to handle the measurement data with care and know the possible sources of error. Also it is important to know how the errors spread through the data processing and affect final results. Modern diagnostic systems involve numerical models of the investigated machine. The models reflect the knowledge about the machine's behavior. They may be of varying complexity depending again on the range of the diagnostics and the available sensors. The models are a set of mathematical or experimental relations that can be used to calculate desired values from the information provided by the measurements. The calculated values reflect the health state of the machine.

The model in the diagnostic system analyzed in this paper involves direct balancing of mass and energy flows in a gas turbine [2, 3]. The equations describe the thermodynamic processes that occur in a turbine. Final results include overall power generation efficiency and several additional indices like isentropic efficiencies of a compressor and an expander. The model is suitable for various models of gas turbines, with one or more expanders (high and low pressure for instance), and with or without a cooling system.

The research described here seeks to determine the range of error in the final results obtained from the model when the input data is corrupted. This is conducted through numerical simulations using an inverted model of a gas turbine [9]. First, an ideal state of an operation is modeled. The values of the parameters in the gas path are calculated [5]. The list of parameters includes pressure, temperature, mass flow rate and gas composition. Then the calculated values are distorted and fed into the diagnostic model, which determines the indices of the health state. The deviations are compared between results obtained for true and distorted measurement data.

The analysis is conducted for gas turbines that are monitored on-line or quasi-on-line. This means that the measurements are immediately processed and the results are added to the knowledge base available to the operator. Therefore the data processing must be done in automatic mode without human supervision and must provide reliable information. Hence the paper also discusses possible solutions to minimize error. These solutions involve simple filtering rules that are applied to raw measurement data before they are sent to the diagnostic model.

A more advanced solution is also shown. It relies on the fact that the dependency between performance indices and the load takes the form of a function (linear, polynomial, etc.). Often this dependency is omitted in the diagnostic process and applied after the health state indices are calculated separately for several load levels—the approximation of the results is the last step of the analysis. The extension to the diagnostic model presented here combines the equations of the model with the shape of the functions that approximate the health state indices. This minimizes the influence of the measurement errors and improves the diagnostic results.

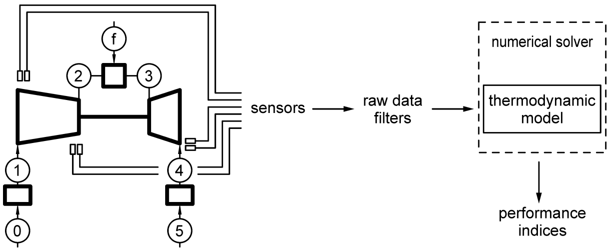

Figure 2: Diagnostic system of a single gas turbine

Table 1: Sensors in a single gas turbine

Symbol	Location	ON-LINE measurements
0	air inlet to the filters	p, T
1	compressor inlet	p, T
2	compressor outlet	p, T
f	fuel inlet to combustor	p, T, m
3	combustor outlet	-
4	expander last stage outlet	p, T, gas composition
5	expander outlet	p, T

2. Diagnostic system

The diagnostic system for gas turbines analyzed here consists of several modules [8]. They are described below with regard to the information involved in the diagnostic evaluation of the machine's performance. The arrangement of the system is shown in Fig. 2.

2.1. Sensors

The number and types of sensors mounted on a machine generally depend on the objective of the diagnostic process. In this paper the diagnostic system is applied to verify the health state of a machine based on performance indices. The sensor system in simple gas turbines usually includes several measurements along the gas path. They are listed in Table 1 with standard symbols for pressure (p), temperature (T) and flow rate (m).

The list in Table 1 shows that the number of sensors is quite low. The main problem is the lack of information about the flow rates. Only the fuel flow is measured directly. The measurement of the air flow is usually not available in industrial turbines and if it is then only during off-line tests. In order to determine the amount of gas in the compressor and the expander, one must use information about the composition of the gas obtained from the lambda sensor. Simple measurement of the CO2 fraction in the exhaust gas can be used to calculate the amount of the flow from the mass and energy balance of the combustor. This indicates that a modeling module is required, as described in the following paragraph.

2.2. Raw data filters

The first step in data processing does not require sophisticated numerical procedures but relies on observing several simple rules of data handling. A brief description of the filters is given in a separate section of this paper.

2.3. Thermodynamic model

The model includes the thermodynamic relations that describe the processes in the turbine. The system analyzed in this paper uses equations of mass and energy balances for the main parts of the turbine rather than correction curves supplied by the manufacturer.

2.4. Numerical solver

The solver uses the information obtained from the measurements to create input data for the thermodynamic model and calculate the required performance indices. The diagnostic procedure described in the following sections of the paper employs the conjugate gradient method. The solver treats the thermodynamic model as a function which calculates the values of gas parameters in several locations of the machine for given values of performance indices. The results are compared against the data from the measurements. The solver algorithm corrects the values of the performance indices in order to fit the measurement data more accurately. When a desired convergence is achieved, the calculations are stopped and the last values of the performance indices are presented as a final result.

3. Simulation of errors

In order to verify the influence of the measurement errors on the diagnostic results a numerical simulation was prepared. The simulation used the model from the diagnostic system, but the solver was inverted. The performance indices were supplied to the solver as input data, while the values measured in a real turbine were calculated. This allowed an ideal state of operation to be simulated without any measurement error. The simulations were conducted for a 56 MW single shaft gas turbine.

Then the error was added to the values obtained from the simulation. The magnitude of the error was controlled and restricted to the assumed range. The values with the error were fed to the diagnostic system and the performance indices were calculated. The difference between the ideal values and the new ones was a measure of the influence of the error. Chosen results of this simulation are presented in Figs 3- 7. Figs 3 and 4 show the isentropic efficiencies calculated for the compressor and the expander when the errors are introduced to the chosen measurements. The measurements are the compressor outlet temperature, the compressor outlet pressure and the expander outlet temperature. The slopes of the lines in the graphs differ, reflecting the influence of the error in the measured value on the values of the performance indices. For example, the error in the compressor outlet temperature affects more the calculations of the isentropic efficiency of the compressor than the efficiency of the expander—the slope of the ΔT2/T2 line is steeper in Fig. 3a than in Fig. 3b with the same relation between Figures 4a and 4b.

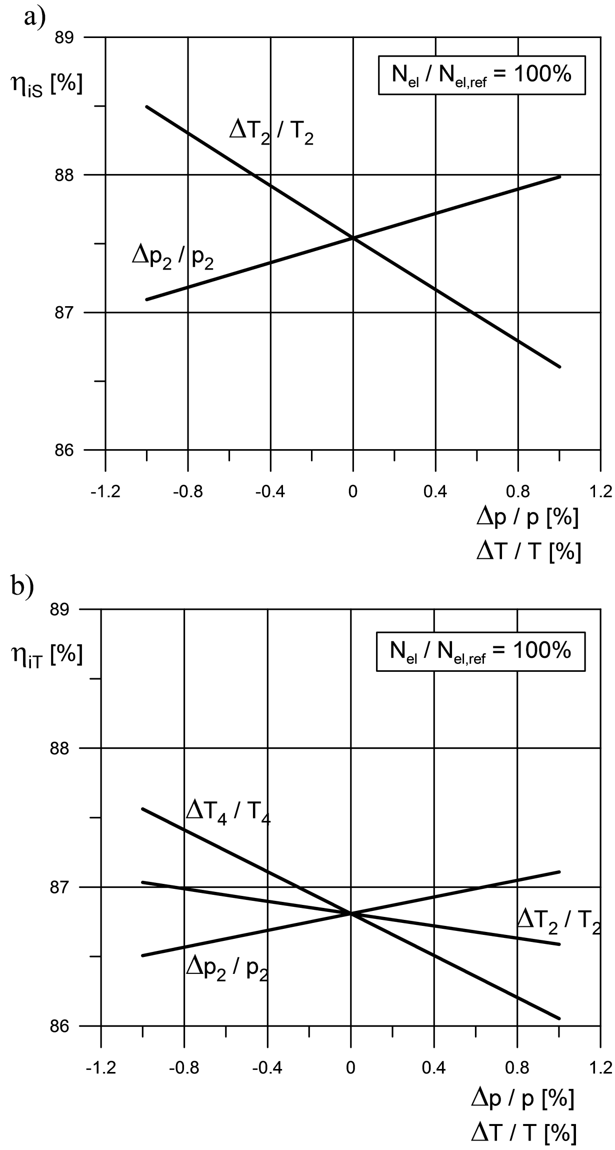

Figure 3: Compressor (a) and expander (b) isentropic efficiencies with measurement errors for 100% load

The compressor outlet temperature affects expander efficiency because the expander is located downstream of the compressor. On the other hand expander outlet temperature does not affect compressor efficiency at all.

The part-load conditions shown in Fig. 4. were simulated using a compressor map and flow-pressure relations for the expander. According to Fig. 4. the influence of the errors

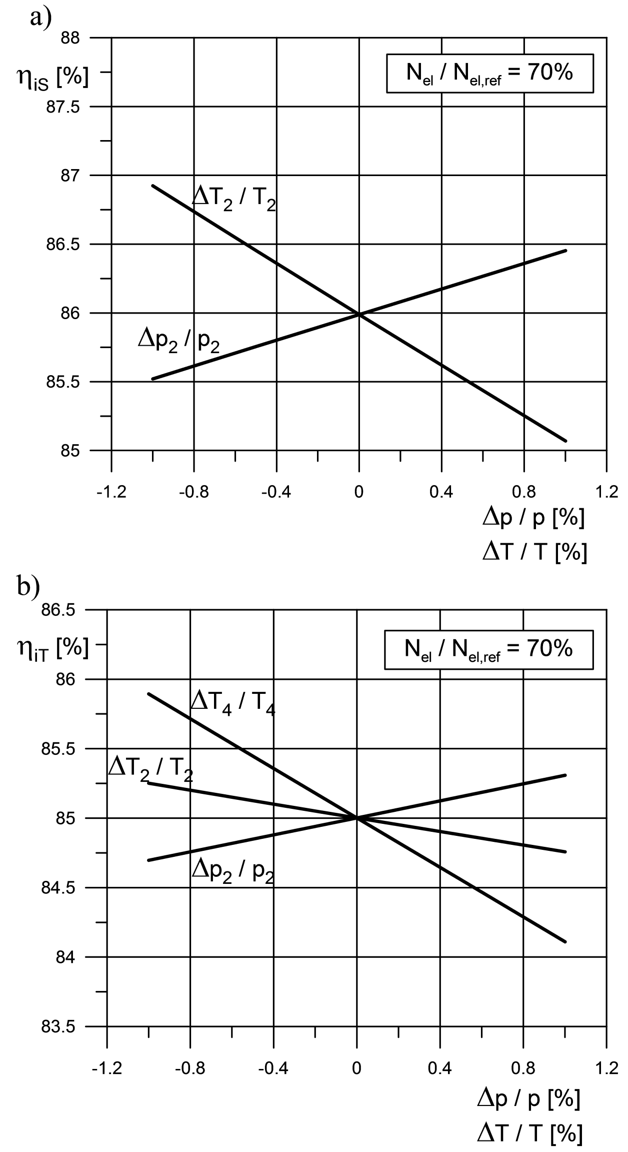

Figure 4: Compressor (a) and expander (b) isentropic efficiencies with the measurement errors for 70% load

in part-load conditions is similar to full load operation. The slopes of the lines in Fig. 3 and 4 are the same, while the range of values at the axes is equal.

More analysis results are shown in Fig. 5. The two lines in the figure relate to the total power generation efficiency of the gas turbine in full and part load operation. Again, the slopes of the lines are the same in both cases. The results from Figures 3, 4 and 5 represent the change in performance indices in relation to ideal conditions, when only one measurement is affected by errors. The combined effect of the errors is shown in Fig. 6 and 7. Figure 6 presents the isentropic efficiency of the expander with artificial errors applied to the compressor and the expander outlet temperature. The correct value of the efficiency is obtained for both ΔT2/T2 and ΔT4/T4 equal to zero.

Similar results are shown in Fig 7 for compressor isentropic efficiency. The graphs are presented again for two load levels. The results indicate that in some cases the errors may compensate for each other and despite their presence the values of the indices are evaluated correctly. However, the effects of the error may also be multiplied.

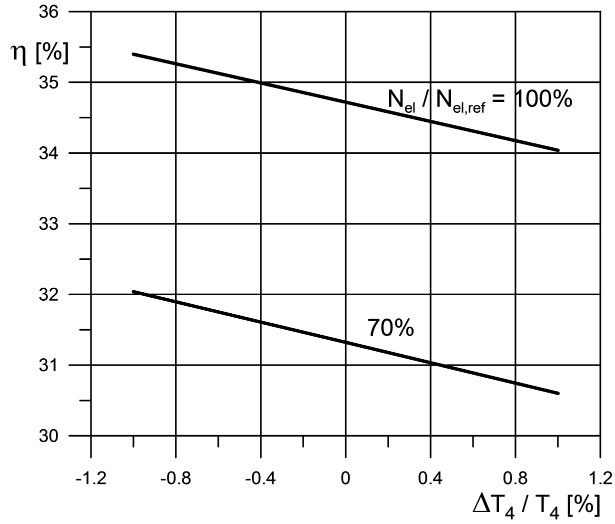

Figure 5: Total power generation efficiency with expander outlet measurement errors at different levels of load

4. Raw data filtering

The first process in data management is a simple filtering of the values from the measurement without any explicit model of the machine. This step is applied before the data are processed in the main diagnostic module according to Fig. 1. Below is a list of the essential filtering techniques that are useful when introducing diagnostic systems and automated data conversion. It is assumed that a set of different measurements is available for a given moment of operation (a point in time).

4.1. Boundaries

In numerical data processing it is advisable to verify a value from a measurement to its minimum and maximum possible values. Very often in automatic data processing, values that are out of range distort the whole analysis. If a single out of range value is identified, then two possibilities exist. Either the system may reject all the values at a given point in time or it may attempt to replace the out of range value with an approximation of the preceding and the following values. The approximation may also be based on the preceding values only. A special case is the lack of a value. This happens when the signal is lost. In this case the missing value should be calculated from an approximation based on several of the preceding values.

4.2. Gradient boundaries

In the power generation process the transition of the operation usually does not happen abruptly. This makes it possible to define minimum and maximum values not only for

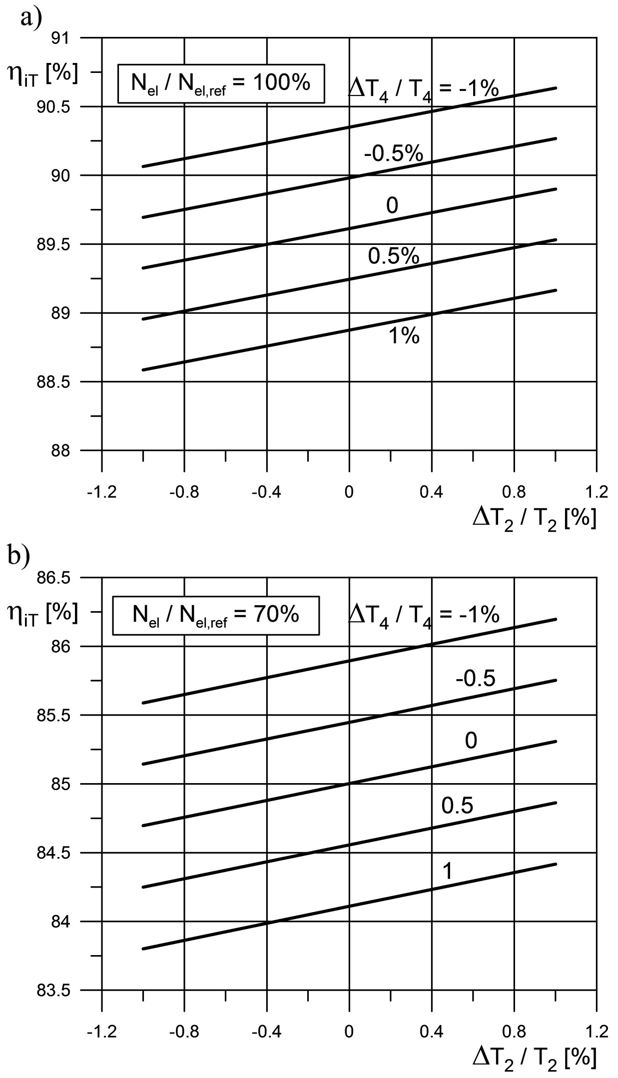

Figure 6: Expander efficiency with measurement errors for various load

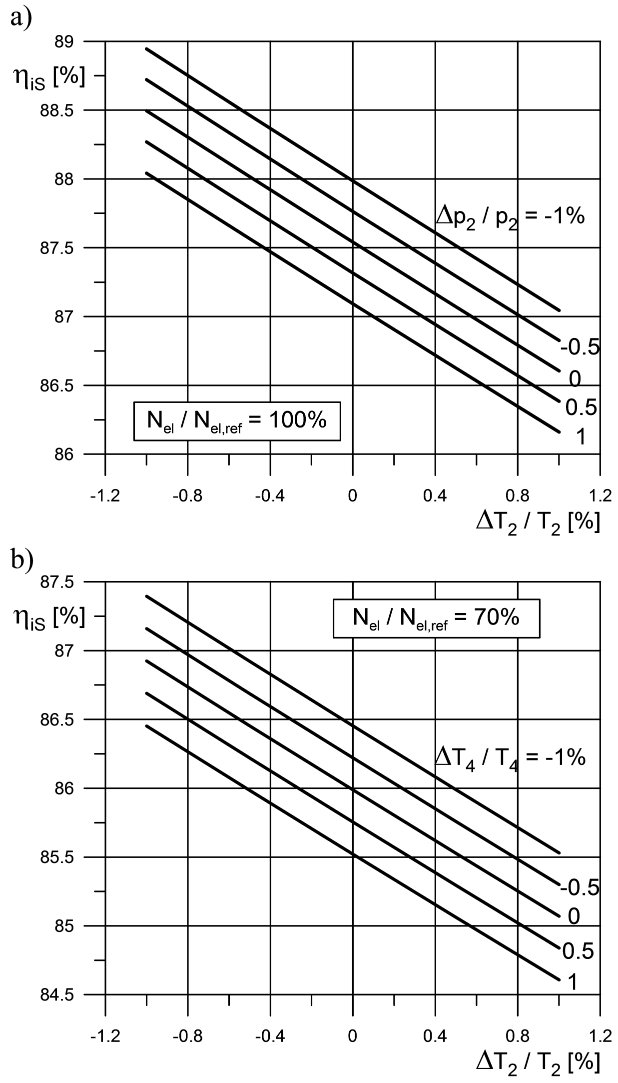

Figure 7: Compressor efficiency with measurement errors for various load

the measured quantities, but also for their gradients, i.e., for their relative change in time. High values of gradients indicate possible measurement error that may correspond to transition states, as described in the introduction.

4.3. Parallel gradients verification

The change in one part of a flow system may usually be observed in other parts. For example, an increase in pressure at the outlet of a compressor results in higher values of the temperature of the compressed flow. The gradients calculated for several parallel values must indicate the same trend. The coupling of the gradients must be carefully chosen, based on the model of machine. This is when the model is applied implicitly—no thermodynamic equation is used but the relations between the measured quantities must be identified.

It must be noted that the filters do not actually eliminate any measurements, but instead set a flag that marks the results as not validated in case a measurement does not meet the above criteria.

5. Enhanced diagnostic system

In typical diagnostic systems the calculations of performance indices are conducted for sets of data for sequential moments of operation ("points" in time). After the calculations are completed, the results are approximated and presented in the form of a dependency, for example between the level of load and efficiency. This approach is understood for a large amount of data or for a single set of data. However, if the measurement data consists of just several sets of data the approximation done at the end of the calculations may lead to a poor evaluation of the actual behavior of the machine.

The method described here assumes the shape of the approximating function before the calculations are started. In the research presented in this paper the functions used in the diagnostic modules were polynomial functions. The minimum number of sets of measurement data depends on the order of the polynomial, just like in the standard approximation procedure, for example at least three sets are required

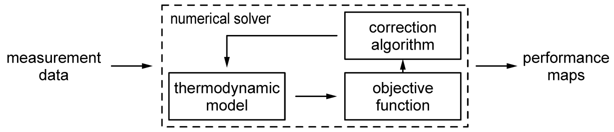

Figure 8: Diagnostic system with the integrated calculation of performance maps

for the order of two polynomial. Any additional set of measurements adds more information about the machine under investigation.

The approximating functions are inserted into the thermodynamic equations of the model of the analyzed machine. The solver (Fig. 2) searches not for the values of the performance indices but rather for the coefficients of the polynomials that represent their approximations. The results include performance maps instead of single values of indices. As written before, the indices are determined in relation to the level of the load.

A comparison of results obtained from the standard and the enhanced diagnostic system is shown in Fig. 9. The results were also obtained from a simulation of the measurement error. First, an ideal simulation was performed. Then the values of the measurements were affected by errors, with the largest error being in the compressor outlet temperature. The artificially created measurement results were passed to the diagnostic system, with and without the integrated performance maps.

The graphs plotted in Fig. 9 show the performance maps for the compressor and expander isentropic efficiency. The efficiencies are related to the load. The line from the enhanced diagnostic system is much closer to the ideal line used in the simulations that generated the measurement data. Since the error in measurement of the compressor outlet temperature affects more compressor efficiency than the expander, the differences between the shapes of the lines are greater in Fig. 9a than in Fig. 9b.

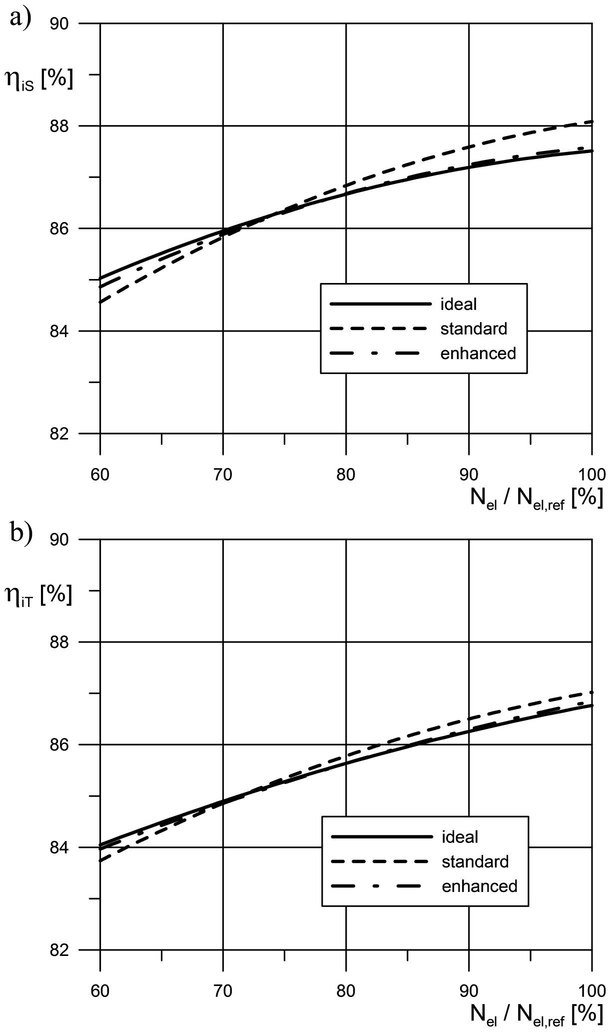

Figure 9: Comparison of performance graphs for standard and enhanced system

6. Conclusions

The application of a diagnostic system with integrated calculation of the performance maps should be considered for quick and accurate determination of the health state, when only several sets of measurements are available. As the number of measurements increases, the results obtained from the enhanced and standard diagnostic systems become similar. It has been observed that the enhanced system produces more accurate results even when the raw data filtering is of poor quality. Insertion of the approximation functions into the diagnostic solver compensates for the low number of repeated measurements and smoothes the resulting performance maps. The most serious limitation of the method is within its definition: the shapes of the approximating functions are defined a priori and there is always the possibility of a wrong prejudgment. Nevertheless, this decision is made based on knowledge of the thermodynamic processes that occur in a machine, so the margin of possible error is small.

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