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113

Selected papers from the International Conference
on *Turbines of Large Output*
devoted to 100th Anniversary of
Prof. Robert Szewalski Birthday,
Gdańsk, September 22-24, 2003

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Transactions of the Institute of Fluid-Flow Machinery have primarily been established to publish papers from four disciplines represented at the Institute of Fluid-Flow Machinery of Polish Academy of Sciences, such as:

- Liquid flows in hydraulic machinery including exploitation problems,
- Gas and liquid flows with heat transport, particularly two-phase flows,
- Various aspects of development of plasma and laser engineering,
- Solid mechanics, machine mechanics including exploitation problems.

The periodical, where originally were published papers describing the research conducted at the Institute, has now appeared to be the place for publication of works by authors both from Poland and abroad. A traditional scope of topics has been preserved.

Only original and written in English works are published, which represent both theoretical and applied sciences. All papers are reviewed by two independent referees.

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TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

No. 113, 2003, 3-4

Editorial

These Special Issues of the *Transactions of Fluid-Flow Machinery*, Nos. 113 and 114 contain selected papers from the International Conference on *Turbines of Large Output* devoted to commemorate 100^{th} Birthday Anniversary of Prof. Robert Szewalski. The conference was held in Gdańsk, Poland on September 22-24, 2003.

The Conference is a continuation of previous conferences held at the Institute of Fluid-Flow Machinery PAS in former years dedicated to technology of steam turbines. Series of conferences bearing the same name took place in the years 1962, 1965, 1968, 1993. In 1997 organised has been a conference on steam turbines and related topics, but with a slightly amended title – *Problems of Fluid-Flow Machinery*. At present at the Institute of Fluid Flow Machinery there are conduced research of fundamental character encompassing both the issues related to steam turbines and fundamentals of power engineering.

Organisers of the present conference have returned to the traditional name, i.e. Conference on *Turbines of Large Output* to mark the respect to the memory of Professor Robert Szewalski (1903-1993), the founder and a director of the Institute of Fluid-Flow Machinery for several years, and initiator of the conference series devoted to the problems of steam turbines.

The Editors are very grateful to the referees of the papers presented in this issue of the *Transactions of Fluid-Flow Machinery*: J. Badur, W. Batko, E. S. Burka, J.T. Cieśliński, P. Doerffer, A. Gardzilewicz, B. Grochal, J. Kiciński, G. Kosman, T. Król, J. Krzyżanowski, J. Mikielewicz, A. Neyman, W. Ostachowicz, R. Puzyrewski, R Rządkowski, J. Świrydczuk, M. Trela, T. Uhl and Z. Walczyk.

We appreciate cordially the manifested authors interest in our conference. Special thanks are conveyed to Ms 'Maya' Bagińska, for her fruitful editorial help related to directing the papers to reviewers and correspondence with the authors of contributions.

Prof. Jarosław Mikielewicz
Editor-in-Chief

Dr Edward Śliwicki
Managing Editor

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KRZYSZTOF BADYDA*, JANUSZ LEWANDOWSKI, OLAF KOPCZYŃSKI
and ANDRZEJ MILLER

A concept of thermo-flow state diagnostic system for steam turbines

Institute of Heat Engineering, Warsaw University of Technology, 21/25 Nowowiejska Str., 00-650 Warsaw, Poland

Abstract

Under normal operating conditions thermo-flow properties of steam turbines vary. This process of deteriorating indicators – except failures – is continuous. That is why a study of the possibility of building continuous diagnosis system has been undertaken. Changes mentioned above are very slow, so it seems advisable to build a steam turbine simulator program. It enables precise study of the influence of particular and complex factors on turbine characteristics changes. Assumptions and general simulator programs structures are presented. With the aid of this tool we investigated the impact of typical damages which may occur in a turbine: gland degeneration and blade salinity. Concept diagnosis based on the change of characteristics is presented. This diagnosis concept was verified and tested using data from simulating program and large data files from power plants archives (DCS).

Keywords: Steam turbines; Thermo-flow state diagnostic system

1 Introduction

1.1 Description

The purpose of this paper is to prepare, work out and verify a concept of thermo-flow diagnostic system for steam turbines. It has been assumed that the developed diagnostic system will co-operate with digital, distributed control system. Nowadays, most power and CHP plant monitoring systems are integrated with DCS's. It means that various process parameters are presented and archived. They include parameters whose values depend on present technical

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*Corresponding author. E-mail address: badyda@itc.pw.edu.pl state of system elements, e.g. efficiency, flow resistance, etc. Next step, making the operation easier, should be the development of diagnostic system which could diagnose technical state of system elements basing on monitored parameter values.

As distinct from solutions used up to now, the developed diagnostic system will not use the values of monitored parameters directly, but rather relative position of present characteristics and a base one – prepared for a new (or repaired) device. It enables taking into consideration the fact that measured values of turbines (systems) and therefore those of monitored parameters are not deterministic, but stochastic. We are of the opinion that the measure of device wear will be such quantities as standard deviation, multidimensional correlating coefficient or appropriate statistic tests [1].

1.2 Wear possibilities of steam turbines

In power steam turbines of medium and large capacity, the wearing processes occur – from diagnostic point of view – slowly. Time scale is of the order of magnitude of ten thousand working hours. Wear caused by unexpected failures is not considered here because of its random character. Wearing processes essentially depend on the method of operation and the quality of media. Method of operation affects possible changes of material properties of elements and possible seal damages. Changes of material properties concern both turbine housings and rotors. They are caused by periodic heating and cooling. Proper operation, keeping suitable rate of temperature changes and proper rotor turning during cooling stage reduce wear to the designed level. Problems connected with this topic are not discussed in this paper. Damages of seals (packing boxes) during operation result from turbine rotor vibrations exceeding allowable values. Causes of excessive rotor vibrations are not important from the point of view of this paper. Seal damages caused by rotor blunting against turbine housing lead to steam leaks. Influence of seal damages on turbine operation will be discussed later in the paper. Problems resulting from the improper quality of agents supplied to steam turbines include mainly poor quality of lubricating and cooling oil and variation of steam properties. Oil properties different from proper ones (e.g. impurities) influence adversely operating properties and conditions of bearings (sleeves). Since operating conditions of bearings are not directly related to thermo-flow properties, influence of improper quality of oil is not discussed in this paper. The last factor – quality of steam supplied to the turbine is one of those parameters which affect turbine operation. Recently, mainly thanks to modern water preparation methods, this problem has become less and less important. However, it is still present in small and medium-size CHP's. Salinity of feed water (too high hardness) results in accumulation of salt deposits on turbine blades. It gives rise to obvious losses described in detail later in the paper. We present possible use of diagnostic algorithms to evaluate degeneration of steam turbines thermo-flow properties, resulting from seal wear and turbine blade salinity. The proposed method has been verified using the steam turbine simulator described below.

2 A concept of diagnostic method

A concept of diagnostic method is based on using large data bases, coming from operating measurements processed by distributed control systems. Proper data selection is fundamental for correct diagnostic process. Unfortunately, slow course of changes rules out direct object analysis [2]. That is why using steam turbine simulator is advisable. With it one can obtain necessary measuring data sets. To get maximal similarity to real conditions, each time a different data set of the same size has been taken – generalized operating point of the turbine set. Three major dimensions along which turbine set operating parameters were determined have been used: measuring instruments class $k = 0.1,\ 0.3,\ 0.5$ and 1.0; degree of gland degeneration $\chi = 1.0,\ 1.2, \ldots 2.0$ and the degree of turbine blade salinity $\omega = 0.95,\ 0.96, \ldots 1.0$.

Degree of gland degeneration χ was determined as

$$\chi = \frac{\dot{m}_g}{\dot{m}_{g0}} \tag{1}$$

where

$\dot{m}_g$ – mass flow through glands gap;

$\dot{m}_{g0}$ – nominal mass flow through glands gap.

Degree of blades salinity ω was determined as

$$\omega = \frac{F_b}{F_{b0}} \tag{2}$$

where

F_b – surface of steam flow through stage;

F_{b0} – nominal surface of steam flow through stage.

The characteristics has been defined in the following way. With the specified class of measuring instruments, for rated gland state and blade salinity a proper model was identified – constants of approximating equation were determined. Elementary characteristics for individual values of χ and ω were determined:

- turbine set power, as a function of live steam mass flow;
- absolute error of approximation, as a function of turbine set power;
- relative error of approximation, as a function of turbine set power.

Keeping the determined constants of the model, cumulative characteristics were found, being generalized characteristics of the above variables χ and ω. On this basis, the following parameters were determined:

- absolute and relative error of the approximate power of the turbine set, as a function of gland degeneration χ and blade salinity ω;
- absolute and relative error of standard deviation of the power of the turbine set, as a function of gland degeneration χ and blade salinity ω;
- correlation coefficient of the observed and approximate power of the turbine set, as a function of gland degeneration χ and blade salinity ω.

Repeating the described procedure for considered measurement accuracy, class k enabled defining general characteristics. As a result, the following relations between the degree of degeneration χ, ω and measuring instruments, class k was obtained:

- absolute and relative error of approximation;
- absolute and relative error of the standard deviation of approximation;
- correlation coefficient of the observed and approximate power.

Specified differences between current and basic characteristics show the degree of losing thermo-flow properties of the turbine set. Relative errors of any value were defined as

$$\delta x = \frac{1}{n} \sum_{i=1}^{n} \frac{x_i - \hat{x}}{x_i} \tag{3}$$

where
x_i – measured value;
$\hat{x}$ – approximated value.
Standard deviation and correlation coefficient are defined in literature.

3 Description of steam turbine simulator

The main reason to develop the steam turbine simulator was the necessity to obtain results usually obtained over long periods. Moreover, archive data do not always have proper form for diagnostic purposes. Acquisition systems usually store values averaged over bands which are not suitable for correct calculations. Finding proper data, so-called "snapshots", requires special preparation of control system software [3].

3.1 Module for selecting operating conditions (pre-processor)

Module for selecting operating conditions of a steam turbine enables users to define in a simple way the range of parameter changes. Besides, it involves simulated damages (salinity or unsealing). When designing a simulator, one of assumptions was to take into account the influence of measuring errors on characteristics shape and measured parameters at the moment of data input. Generator of initial vector coordinates – pressures, temperatures, etc., attached to the simulator module, gives values of normal distribution oscillating around the operating point with fixed standard deviation and a cut-off due to exceeding parameter values (technical limitation). Uncertainty of values for each element obtained in this way is limited by user defined class of measuring devices and is applied further in diagnostic process.

3.2 Module for turbine calculations (processor)

Calculating parameters of a steam turbine is conducted using the sequence – iterative method [2]. The turbine is divided into groups of stages. Quantities are given for each characteristic point, including: inter-group spaces, extractions, control valves etc. The simulator module includes: parameters i.e. physical properties of elements, e.g. diameters, and quantities whose values can be fixed or changeable, depending on the kind of characteristics, e.g. efficiency or mass stream. Due to calculation rate, mathematical model does not take into account physical dimensions and is based on properly averaged values. The whole simulator module has a structural character, processing local calculations and characteristics using independent functions. It enables easy characteristic change and fast control of the algorithms of global calculations. To determine properties of steam and water, numerical procedures compatible with *International Water Skeleton Tables* have been used. These procedures were worked out at the Institute of Heat Engineering, Warsaw University of Technology [4]. Modular software structure enables changing the procedure, if need be.

3.3 Module for segregating and preparing data (post-processor)

Similarly to input data, output data must have proper structure and properties. That is why output data processing module has been attached, to filter information coming from the simulator and giving only information related to the parameters set by the user. According to the assumption concerning uncertainty of measurements and readings, output data also involve errors. It is important that, in case of giving enthalpy, the error is not applied to the value of enthalpy, but to the measured values, used to determine the enthalpy (e.g. pressure and temperature). Data prepared in this manner are written into user named files, to allow further processing. Additional procedures have been worked out to enable determination of selected statistical properties of processed data. The whole simulator program has a modular structure, which enables various operating configurations, including totally deterministic determination of the parameters of a turbine set and passive monitoring without any diagnosis.

4 Investigating the influence of gland degeneration χ

The model of turbine set simulator takes into consideration the influence of increasing size of a gap between blades and the housing. It applies both to internal and external glands. In case of internal glands, deterioration of the internal efficiency of stage groups is responsible for internal efficiency drop – this simplification is allowed because the final effect – power drop – follows from the product of internal efficiency, mass flow and isentropic enthalpy drop. That is why substituting decreasing mass flow by limiting internal efficiency is justified, if we are aware of primary reasons of the effect. Losses caused by increasing running clearance in external glands are defined in the simulator directly, by calculating steam leakage and proper corrections of steam mass stream, supplied to appropriate groups of stages. Algorithms used to estimate the quantity of leaked steam have been taken from literature (Russian papers and library dependencies available at the Institute). All the dependencies are based on the gas outflow through a small hole – convergent orifice – and take into account corrections for the flow through a gap. Any differences consist only in the number of corrections (small) and their values (even smaller). None of the formulae takes directly into account the influence of shaft rotation and steam whirling which has of course non-zero viscosity. Analysis of elementary gland model with the aid of commercial software – FLUENT – confirms the fact that the results are consistent with the formulae. Many years' experience and computer simulations prove that using the above procedures is fully justified.

4.1 Examples of relations

The possibility of diagnosing gland degenerate state has been shown in Fig. 1, on the basis of power approximation error. One can clearly see monotonous increase of power approximation error with the increased gland clearance. Results of calculations practically do not depend on the class of measuring instruments. Increasing approximation error towards negative values is consistent with physics of the effect, i.e. power loss due to increased losses. Good and uniform correlation of diagnostic values (Fig. 2) does not justify rejecting the hypothesis of correct diagnostic process.

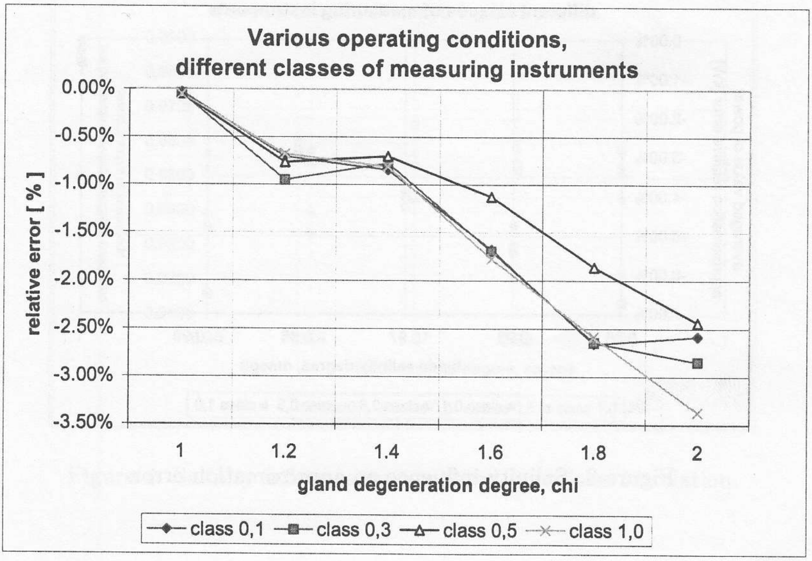

Figure 1. Influence of gland degeneration on approximation error.

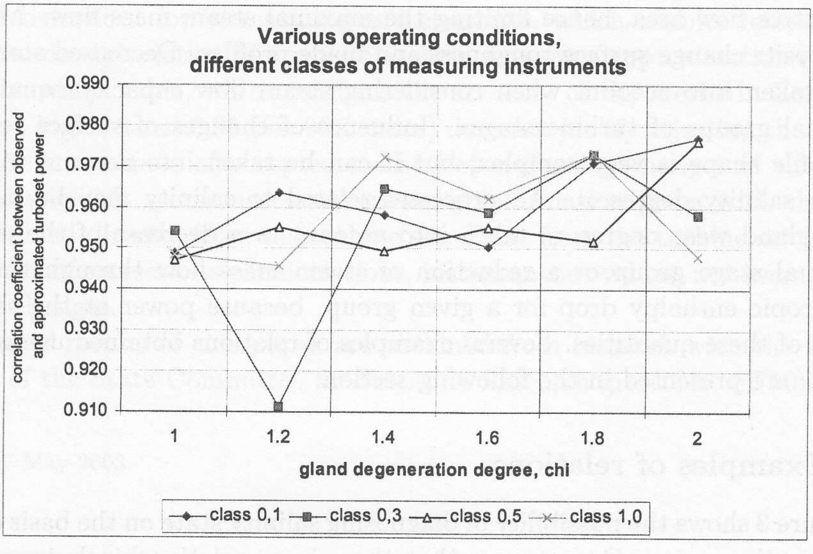

Figure 2. Glands degeneration influence on compared quantities correlation.

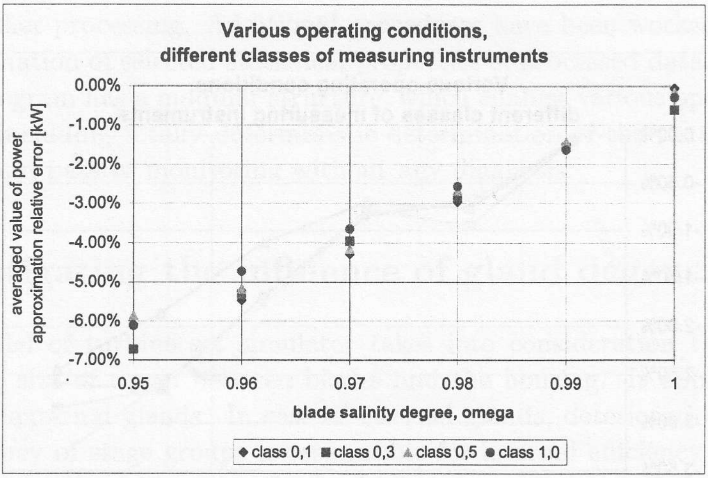

Figure 3. Salinity influence on approximation error.

5 Investigating the influence of blade salinity ω

The turbine set simulator model takes into consideration the influence of blade-ring salinity. It applies mainly to last groups of stages of LP housings. However, it also affects operation of the whole turbine set. Salinity decreases the effective flow area, hence limiting the maximal steam mass flow. Moreover, salt deposits change surface roughness and blade profiles. Decreased steam mass flow is taken into account when considering steam flow capacity equations for individual groups of turbine stages. Influence of changes of surface roughness and profile shape is very complex, but it can be taken into account increasing effective salinity degree ω. All processes related to salinity may be, as in the case of gland wear degree χ, taken into account in a decrease of the efficiency of internal stage group or a reduction of steam mass flow through this group or isentropic enthalpy drop for a given group, because power at the shaft is a product of these quantities. Several examples of relations obtained using salinity degree ω are presented in the following section.

5.1 Examples of relations

Figure 3 shows the possibility of diagnosing salinity state on the basis of power approximation error. One can see that there is no relationship between power approximation error and measuring instrument class, which is an extra argument for diagnostic possibilities. Good and uniform correlation of diagnostic values (Fig. 4) does not justify rejecting the hypothesis of correct diagnostic process.

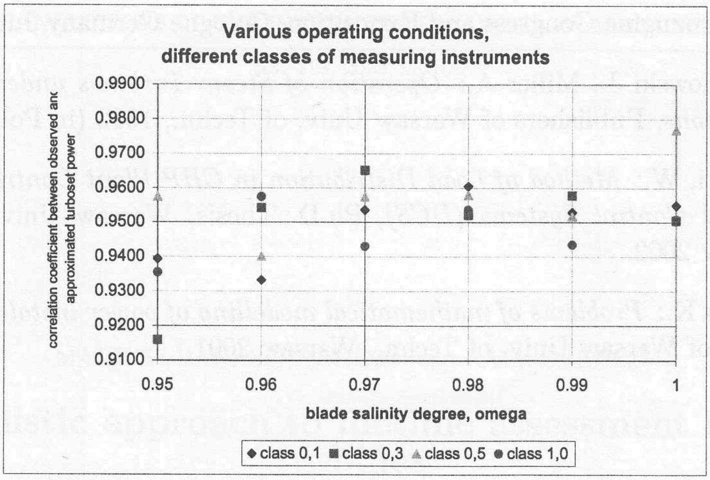

Figure 4. Salinity influence on compared quantities correlation.

6 Conclusions

Calculations suggest accepting the proposed method of evaluating the difference between real properties of a turbine set and rated values. The investigated values of approximation errors for various classes of measuring instruments show coherent behaviour for increasing gland clearance, which enables relevant diagnosis. Standard deviation of errors of turbine set power approximation oscillates around constant value, which confirms the stability of the method. Correlation coefficient higher than 0.95 (for 90% cases) does not justify rejecting the hypothesis of the correctness of accepted method of evaluating changes of turbine set characteristics. It seems necessary to verify information given with the aid of data obtained directly from the turbine set. Data from the turbine set must be, for the sake of correctness of calculations, instantaneous values, not averaged over range of changes.

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3 Sources of uncertainty in deterministic approach

Many years' experience of numerous laboratories shows that the scatter of properties for most high-temperature creep resisting steels is in the range of ±20% of mean values of creep rupture strength and creep limit. The corresponding scatter in time reaches several hundred percent [5]. This approximate character of experimental data and resulting limitations in full use of extrapolated values result from:

- heterogeneity of the material and differentiation in chemical composition, structure and heat treatment of the same materials at different melts,
- errors in creep tests (control and measurement of temperature and stress),
- differentiation in operating conditions and the influence of environment as compared to laboratory parameters,
- existence of physical variation of phenomena occurring in short-term tests and during service,
- impact of technological and design factors on the material lifetime.

For example, creep tests are done in air at elevated temperature where oxidation effects adversely affect the strength of steels. In actual conditions, the oxidation effect with reference to a large section of rotor, for example, may be negligible [2]. Typical examples of scatterband of creep rupture strength for cast steel used for casings is shown in Fig. 1.

A similar trend is observed in fatigue characteristics of turbine steels. Typical scatterband of total strain amplitude in low-cycle fatigue is on the level of ±10% of strain mean value.

The above factors make the lifetime assessment, based on deterministic model and minimum strength properties, very conservative.

An additional factor introducing uncertainty into the deterministic model is the averaging of operating conditions. The lifetime studies are performed for typical start-ups from a cold, warm and hot state, prepared from an extensive operating data provided by the turbine user. An example of the analysis taking into account the scatter of operating parameters in determining stresses in 200 MW turbine stop valves is presented in reference [6].

4 Probabilistic method of lifetime assessment [7]

The probabilistic methodology of lifetime assessment is based on laboratory testing where the scatter of creep and fatigue properties of turbine steels can be described by log-normal distribution. Based on the data contained in the