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An expert system concept for diagnosis and monitoring of gas turbine combustion chambers

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Abstract

In this paper, the main principles of operation, the conceptual design and the development of an expert system for fault diagnosis and monitoring of gas turbine combustion chambers are presented. The concept of the gas turbine chamber expert system is based on the monitoring of the spatial and temporal distribution of the heat flux inside the combustion chamber and the simultaneous comparison of respective readings of diagnostic variables with values obtained through numerical model simulation of different situations which lead to the malfunction of combustion chamber and deterioration of its performance. The demonstration of the expert system will be performed at the VTI (All Union Energy Institute, Russia) gas turbine combustion chamber test facility.

Keywords: Expert systems; Gas turbines; Combustion chambers; Diagnostic strategy

1. Introduction

The future energy strategy in Europe will be based on the increased use of gas for electricity production. Gas turbine electricity generation units consist of the foundations of this strategy [1]. The number of gas turbine plants will increase in all power ranges. In particular, small and mini gas turbine plants will become strategically an important part of the energy systems. The efficiency and reliability of those units will require sophisticated surveillance and control. It would be very difficult to have a large number of different expert systems to support these units. For this reason, the development of prognostic and diagnostic systems will be of great importance. The deficiency in expert manpower for gas turbine surveillance may become a limiting factor in the further development of energy systems based on small and mini gas turbine units. Bearing in mind that reliability of gas turbine units is very important for their introduction into the energy systems, the development of expert systems similar to the one described in this paper may actively contribute to the confidence in small and mini gas turbine introduced in local, regional and global power generation systems. The European added value of this concept is realised by the promotion of efficient and reliable small and mini gas turbines with prognostic and diagnostic systems supported by remote expert surveillance.

The combustion process in a gas turbine combustion chamber is a very complex process with a number of physical and geometrical variables affecting its performance. The total heat flux on the combustion chamber

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walls is an integral parameter reflecting the changes of the combustion process inside the chamber. The variation of the heat flux in space and time is a result of the spatial and temporal distribution of a number of parameters affecting the combustion process. In this respect, the aforementioned changes may lead to undesired operating conditions and to the malfunction of the system. The diagnosis of these situations is of great importance to the user of the gas turbine who aims to maximise its efficiency and reliability. In particular, malfunction of the gas turbine combustion chamber is associated with instability of the flame and its distortion due to burner malfunction.

Consequently, the present research work contributes towards the utilisation of monitoring the heat flux as the main input to the expert system instead of using alternative variables. The above monitoring process is carried out with the utilisation of a new heat flux sensor. The expert system performs a number of tasks such as diagnosis of pulsating regimes inside the combustion chamber, control of low-emission operation for exit concentration of NO_x less than 50 mg/N m^3, monitoring of the reliability of the combustion process in several regimes of combustion chamber operation, monitoring of the lifetime of the combustion chamber, control of the flame flashback into the premixing zones.

2. The concept of the diagnostic and monitoring system

The expert system of the gas turbine combustion chamber diagnostic system is based on a new heat flux sensor [2,3] and the corresponding evaluation of the readings of the monitoring system. The new method is based on the use of a convectively cooled porous sensing element, as illustrated in Fig. 1.

The high temperature gas flows over the porous element and promotes heat transfer to the element surface through convection and radiation. The cooling gas, flowing through the porous element, is heated due to the heat transfer from the hot gas, via the porous matrix so that

$$q_{\text{tot}} = q_{\text{con}} + q_{\text{rad}} = j \cdot c_{\text{p}} \cdot \Delta T$$

At the critical gas flow rate j_{crit} the hot gas boundary layer will be blown off so that the heat flux due to convection will disappear, $q_{\text{con}} = 0$, and the total heat flux will become equal to

$$q_{\text{tot}} = q_{\text{rad}} = j_{\text{crit}} \cdot c_{\text{p}} \cdot \Delta T_{\text{R}}$$

Repeating the same measurement procedure at the gas flow rate $j < j_{\text{crit}}$, the following relation is valid:

$$q_{\text{tot}} = q_{\text{con}} + q_{\text{rad}} = j \cdot c_{\text{p}} \cdot \Delta T$$

so that the convection part of the heat flux could be determined by

$$q_{\text{con}} = q_{\text{tot}} - q_{\text{rad}}$$

Experimental demonstration of the heat flux sensor has proven its versatility for various potential applications at the required accuracy.

The combustion process in the gas turbine combustion chamber is a very complex process with a number of physical and geometrical variables influencing its performance. The total value of the heat flux on the combustion chamber walls is an integral parameter reflecting the changes that may occur in the combustion process inside the chamber. The spatial and temporal distribution of the heat flux is the result of the values of the aforementioned parameters that determine the combustion process. In this respect, certain parameter settings may lead to undesired operating conditions of the system. The diagnosis of those situations is of great importance for maintaining high efficiency and

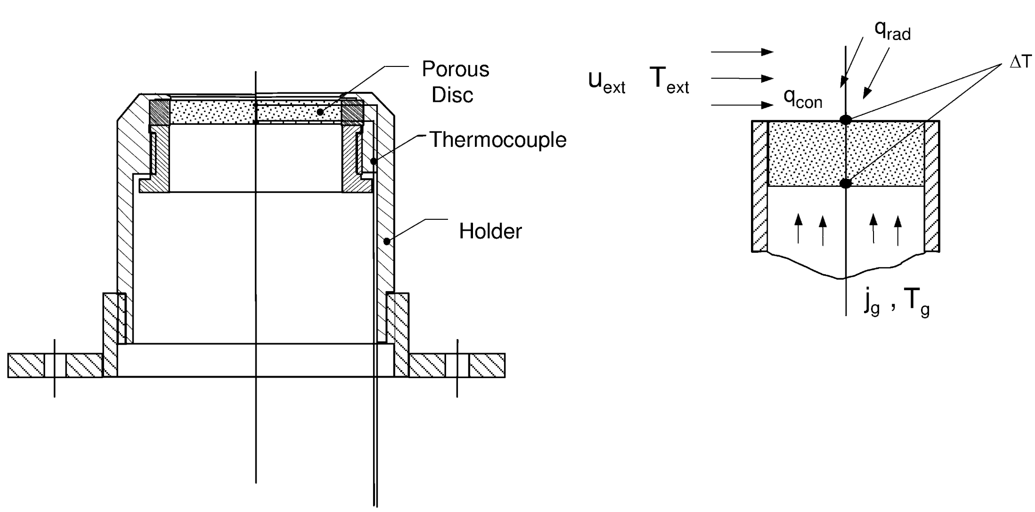

Fig. 1. Convectively cooled porous element sensor.

reliability of the gas turbine system. In particular, malfunction of the gas turbine combustion chamber is affected by instability of the flame and its distortion due to burner malfunction.

The gas turbine control system includes sequencing, control, protection and operator information, which provides for orderly and safe start-up of gas turbine, control of proper loading and an orderly shutdown procedure. In addition, it includes an emergency shutdown capability, which can operate automatically by suitable failure detectors or manually [4]. Coordination between gas turbine control and driven equipment must be provided for start-up, operation and shutdown.

3. The concept of the expert system

Presently available knowledge-based systems used for diagnostics of gas turbine system performance are based on the monitoring and processing of a number of control variables [5]. These variables reflect integral processes in the gas turbine system. Fault diagnosis in these systems is aimed towards detecting those situations, which are of general nature and reflect events, which have either already taken place in the system or have been degrading the gas turbine system elements.

The stability of the flame in the gas turbine combustion chamber is an immanent problem in the gas turbine operation. There are two approaches to the flame stability problem, the first one is based on the organisation of the combustion process in the chamber with high gas velocity and respective flow arrangement inside the chamber and the second approach is based on introduction of a diagnostic system which recognises the change of characteristic parameters in the combustion chamber responding to flame instability. The current diagnostic system of gas turbine combustion chambers detects and also predicts flame instability. In addition, diagnostic variables are used for the lifetime assessment of combustion chambers and of the first blade row of the downstream turbine unit.

The diagnostic strategy is organised to recognise the following main operational situations:

1. Diagnosis of pulsating regimes inside the combustion chamber (combustion noise).
2. Control and diagnosis of low-emission combustion chamber with outlet NO_x concentration less than 50 mg/N m^3.
3. Diagnosis of low-NO_x combustion chamber operation with temperature level up to 1500–1700 K.
4. Monitoring of reliable combustion at various regimes of combustion chamber operation.
5. Assessment of lifetime of combustion chamber and first row of gas turbine blades by monitoring gas temperature.
6. Control and monitoring of the circumferential gas temperature distribution at the turbine outlet.
7. Control of the flame breakthrough to the premixing zones.

4. The expert system for the gas turbine combustion chamber

The basic concept of the gas turbine chamber expert system is based on the monitoring of the space and time distribution of heat flux and temperature in the combustion chamber and the comparing of diagnostic variables with values obtained through numerical model simulation of different situations that may occur and can lead to the malfunction of combustion chamber performance.

Monitoring systems, knowledge bases, knowledge-based systems and display systems are elements of the diagnostic system. The composition of the diagnostic system structure is designed to perform the following functions:

- Continuous monitoring and diagnosis of gas turbine combustion chamber.
- Comprehensive fault detection.
- Multilevel diagnostics to permit time dependent forecast of failure.
- Assessment of the effect of the fault on the performance of the gas turbine system.
- Special feature of the diagnostic system with lifetime assessment of gas turbine combustion chamber and first row of turbine blades.

The expert system is composed of the following elements.

4.1. Monitoring system

The monitoring system comprises of heat flux sensors distributed at specific locations in the combustion chamber and an acquisition system with respective software for signal conditioning and verification. It also includes buffers for data storage.

4.2. Knowledge base

The knowledge base represents a set of data obtained through three-dimensional numerical simulation of the gas turbine chamber and organised in the structure of elements representing situations to be analysed by the system. The 3-D numerical model of a gas turbine combustion chamber comprises a numerical solution tool of a set of discretised equations including mass, momentum and energy balances for the control volume of discrete elements of the system. The model represents the generic simulation of space distribution of parameters in the system. This simulates different malfunction situations of the combustion chamber and defines the knowledge-based system. The data obtained represent the possible situations to be retrieved by the diagnostic system.

4.3. Knowledge-based system

The knowledge-based system is a data processing software with a logically structured inference engine for data retrieval. The data obtained at every cycle of data acquisition represents the input data for the inference engine to be processed in accordance with a retrieval procedure. The retrieval procedure of the knowledge-based system is a set of rules to recognise those situations which are the most probable situations corresponding to the individual reading. Every situation obtained in the retrieval procedure is displayed with its respective probability assessment of diagnostic confidence.

4.4. Display system

The final stage of the diagnostic procedure is the display of the obtained situations and prognoses for the further development of the failure. In this respect, the display elements consist of a subsystem of the diagnostic system.

5. Set-up of the expert system

The concept is set-up as follows.

5.1. The basic concept of the diagnostic system based on the heat flux pattern in the gas turbine combustion chamber

A new method for heat flux measurement [4] is adapted for practical deployment as a heat flux sensor in the gas turbine combustion chamber. The method is based on a new sensor, whose reliability in long-term operation at high temperatures has been already demonstrated. Thanks to its small overall dimensions and very short response time, the sensor can be easily adjusted for gas turbine on-line monitoring. The heat flux pattern recognition is represented in object form and used for retrieval of specific conditions in the gas turbine combustion chamber.

5.2. The monitoring system

The gas turbine monitoring system is based on the heat flux measurements integrated with the help of a validation procedure, specifically designed according to a diagnostic strategy. A selected number of instruments are positioned in accordance with guidelines suggested by the structure of the specific domain knowledge-based system gained by expert operators [5]. The data validation procedure essentially consists of a statistical analysis of the quality of the data.

5.3. The knowledge-based system for the gas turbine combustion chamber diagnostic system

The design of the knowledge base comprises selection of the potential situations, which are to be recognised in the retrieval procedure. The respective number of the heat flux pattern readings describes these situations. In order to obtain the heat flux patterns for the specific situations, a 3-D numerical simulation code for gas turbine combustion chambers is used. In accordance with the diagnostic strategy of the system, a number of situations with respective heat flux patterns are generated and presented in the knowledge base [6,7]. The test facility combustion chamber is equipped with a number of temperature measurement sensors for the control of the gas outlet condition.

Among the situations to be investigated are the following: instability of LHV gas combustion; burner failure development; lifetime monitoring of combustion chamber and gas turbine first row blades; variation in combustion regimes; low NO_x combustion operation; high temperature regimes of combustion chamber.

5.4. The diagnostic procedure

The diagnostic procedure includes the monitoring system for reading and conditioning of the diagnostic parameters, the development of an appropriate numerical model for the gas turbine combustion chamber, the design of the knowledge base of fault detection, and a decision-making procedure to handle quality assurance, design reliability and to support the persistence of information [8]. The test facility with the combustion chamber is used as the standard pattern for the numerical model to be used in gas turbine diagnostic system. The fuzzification of the diagnostic variables leads to the use of fuzzy logic for the assessment of respective situations.

The diagnostic and monitoring system for the gas turbine combustion chamber [9,10] is shown in Fig. 2.

5.5. Implementation and calibration of the prognostic and diagnostic system

The actual implementation and calibration of the prognostic and diagnostic system for the on-line monitoring of the combustion chamber of a turbo-gas set will be performed on an experimental facility. As shown in

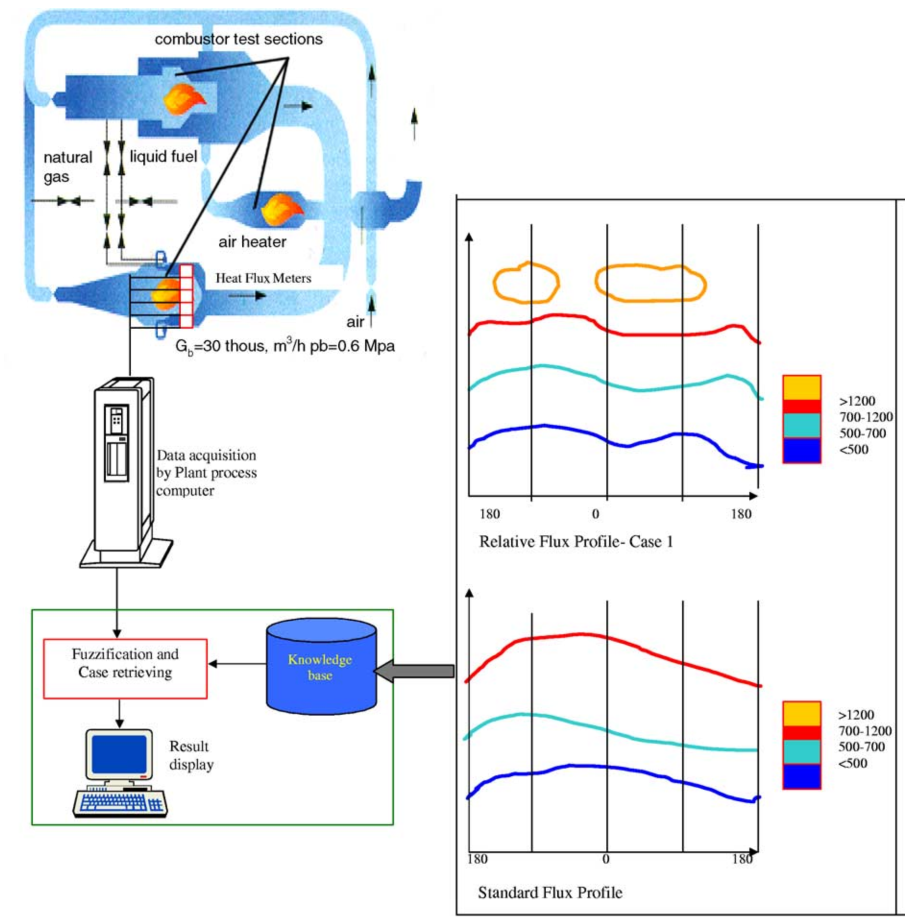

Fig. 2. Diagnostic and monitoring system for gas turbine combustion chamber.

Fig. 2, the VTI test facility will be specially designed for experimental work including a gas and liquid fuelled combustion chamber. This is equipped with a control system with corresponding instrumentation for the control of integral parameters of the turbine combustion chamber. It includes verification of the monitoring system and a corresponding validation procedure. The amount of data in the knowledge base is kept within workable bounds simply by limiting the number of selected situations, which describe the most probable faults.

6. Conclusions

The concept of a prognostic and diagnostic expert system for the gas turbine combustion chamber is a tool, which supports efficient and reliable gas turbine operation as well as remote surveillance and monitoring of gas turbine systems. Since high-level expertise is becoming scarce in energy systems, the development of the prognostic and diagnostic expert system for gas turbine combustion chambers will become an ultimate goal of the future energy system.

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