FAILURE MODE DETECTION OF FEEDWATER HEATERS IN OPERATIONAL CONDITIONS BASED ON THE SIMPLIFIED FIRST-PRINCIPLE MODEL

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Summary

This work presents a model-based methodology for failure mode detection of feedwater heater line working in coal-fired power unit. The main objectives of this work are as follows: (i) introduce the problem of feedwater heater diagnostics, (ii) discuss techniques used for failure modes detection, (iii) introduce a diagnostic method based on mathematical model of a feedwater heater, and (iv) validate the method basing on real operational data from a 225MW power unit. The reason for developing a new methodology is that conventional methods, which are currently used, are not efficient and do not ensure early fault detection. Therefore a more advanced approach based on adjustable phenomenological parameters (i.e. heat transfer coefficients), that are estimated from measurement data, is proposed.

Key words: failure mode detection, feedwater heater, model-based diagnostics.

WYKRYWANIE USZKODZEŃ PODGRZEWACZY WODY ZASILAJĄCEJ W WARUNKACH ESPLOATACYJNYCH NA PODSTAWIE UPROSZCZONEGO MODELU

Streszczenie

W pracy przedstawiono metodologię wykrywania awarii podgrzewacza wody zasilającej pracującego w jednym z bloków elektrowni węglowej. Główne cele prowadzonych badań są następujące: (i) omówienie problemu diagnostyki grzejnika wody zasilającej, (ii) omówienie technik stosowanych do wykrywania awarii podgrzewaczy, (iii) wprowadzenie metody diagnostycznej opartej na matematycznym modelu podgrzewacza wody zasilającej, oraz (iv) weryfikacja metody w oparciu o dane zarejestrowane na 225MW bloku energetycznym. Powodem opracowania nowej metodologii jest to, że konwencjonalne metody, które są obecnie stosowane, nie są skuteczne i nie zapewniają dostatecznie wczesnego wykrywania usterek. Dlatego tez w pracy zaproponowano bardziej zaawansowane podejście oparte na dostrajaniu modelu (np. na współczynnikach przenikania ciepła) w oparciu o dane pomiarowe.

Słowa kluczowe: wykrywanie przyczyn awarii, podgrzewacz, diagnostyka oparta na modelu.

NOMENCLATURE

$\dot{m}$ [kg/s] - steam mass flow

$\dot{m}_w$ [kg/s]- feedwater mass flow

T_{w1}, T_{w2} [°C]– feedwater temperature respectively on inlet and outlet from the heater p_{w1}, p_{w2} [Pa]- feedwater pressure respectively on inlet and outlet from the heater

Ts [°C]– steam temperature

k [W/(m2*K)] – heat transfer coefficient

F [m2] – area of heat exchange

c_p [J/(kg*K)] – specific heat of feedwater

1. INTRODUCTION

Great advances in control and monitoring systems applied in thermal power plants have created a possibility to develop new efficient methodologies for diagnostics and condition assessment of power unit components. At the same time, increasing attention to safety and need for reduction of energy production costs have made a demand for such new methods.

This paper focuses on the performance 225MW power unit, being a subsystem of a power plant located in Polaniec, Poland. In particular, operation of a high pressure heater line is considered.

For detailed description of thermal power plant's regeneration circuit see [1] or [4].

The aim of the research was to provide a method that will enable quick detection of heater failure modes, basing on historical data. The engineering need standing behind this research is that performance of currently used diagnostic methods require improvement regarding early-warning towards typical malfunctions, such as tube bursting inside a heater or servovalve faults. Those methods are based on observation of measured operational parameters, and, as a result, they are not precise and do not ensure early detection of faults. At the same time, proposed method is able to detect symptoms of fault.

To achieve the goal, real operating data concerning operation of high pressure heater line was gathered from the power plant archives. The data taken into consideration corresponds to one year of operation, with sampling interval equal to five minutes. Additional data concerning periods, types and reasons of heater malfunctions was also analysed with relationship to raw data.

2. HIGH PRESSURE FEEDWATER HEATER INSTALLATION

1.1. Principle of operation

Typical regeneration system is shown in figure 1. Feed pumps pass the condensed steam (feedwater) from a condenser through heater banks, supplied by the steam extracted from the high, intermediate and low-pressure sections of a steam turbine [2]. The condensate is pumped to the deaerator, through the bank of low-pressure heaters XN1, XN2, XN3, XN4 and XN5, and further from the deaerator to the steam generator (boiler) through the bank of high-pressure heaters XW1, XW2 and XW3.

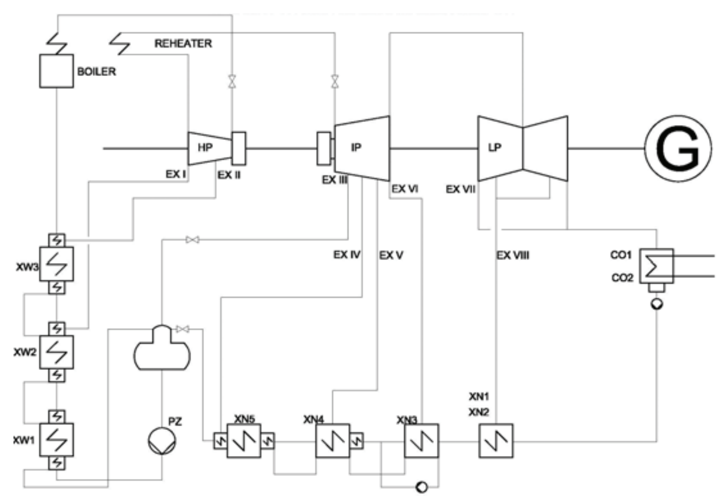


Fig. 1. Functional scheme of a power block [2]. (EX: steam extraction port; XW: high pressure heater; XN: low pressure heater; CO: condenser; PZ: main pump)

The drainage system of the feedwater heater consists of a drain removal path from each heater. The normal drain flow path is cascaded to the next lower stage heater, and the alternate path is diverted to the condenser. The heaters XN1 and XN2 assembled in the condensers are in continuous operation with the condensers CO1 and CO2. When the turbine is loaded at a given rate, steam is allowed to enter the bank of high-pressure heaters through extraction outlets and pipelines denoted by III, II and I to the heaters XW3, XW2 and XW1, respectively.

Feedwater heaters are typically designed as three-zone heat exchangers with a condensing section, desuperheater and integrated subcooler (Fig. 2).

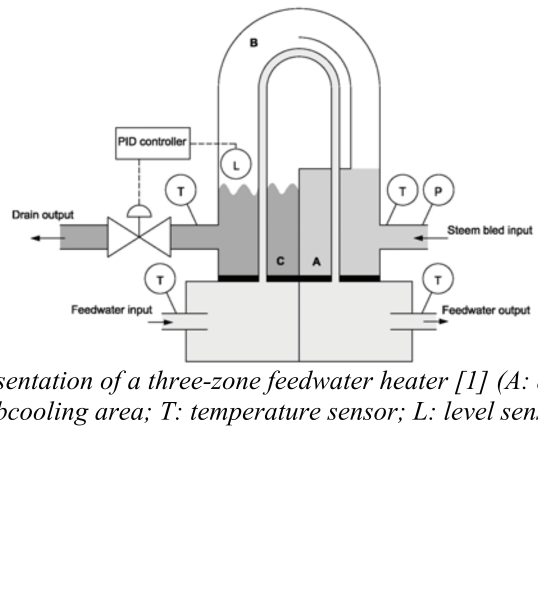


Fig. 2. Schematic representation of a three-zone feedwater heater [1] (A: desuperheating area; B: condensing area; C: subcooling area; T: temperature sensor; L: level sensor; P: Pressure sensor)

1.2. Control system of high pressure heater line

Regulatory control loops of the condensate level control are coupled to the power unit controller. The control system consists of the PID controller, which enables the condensate level variation to be compensated and maintains its constant level in the subcooling zone. Feedwater temperature control is realised by the steam pressure control valves regulating the pressure of the steam entering the heater [2].

Supervisory control over the whole heater line is realised by a SCADA (Supervisory Control And Data Acquisition) system.

1.3. Common malfunctions of a high pressure heater

Reliability of feedwater heaters is strongly influenced by their design, applied materials and operating conditions [8]. Most common faults of heaters concern piping systems. Tube bursting makes the feedwater flow into the external jacket of the heater, and consequently feedwater gets mixed with condensate. The leakages have several causes: (i) electrochemical corrosion, (ii)erosion caused by water or steam, and (iii) fatigue – due to mechanical vibrations. Details of each cause of fault, common places of occurrence and discussion on materials for heater's construction are provided in [8].

Moreover, operation of the heater may be influenced by faults of auxiliary devices, such as three-way servovalves regulating flow of fluids through the heater. There occur also malfunctions of control system elements, e.g. sensors measuring operational parameters of the heater and giving information to the controller.

Consequences of consecutive malfunctions for the whole power unit are described in [1].

2. DIAGNOSTIC TECHNIQUES CURRENTLY USED IN POWER PLANTS

In order to establish what techniques for heater condition assessment are practically used in power plants, a brief survey was made. On the basis on information obtained from a power plant representative the following conclusions have been made.

It is expected that the condensate level will always be constant. However, there are set two safety thresholds regarding that level: 500mm (warning) and 2000mm (faulty conditions). A possible malfunction, typically leakage of feedwater into external jacket of heater, is detected basing on observation of trends of opening of drain valve. Any leakages in feedwater circuit will generate an increase of condensate in the heater. That increase must be compensated by greater opening of a drain valve. If the value of drain valve displacement is quite different than normally the heater is considered to be faulty.

However, detection of heater fault is not always equal with shut-down of the whole unit. Typically, only few pipes are damaged. Influence of such fault on the heater performance is not significant until the regulator is able to compensate for the leakage. In those cases, heater usually operates till the next scheduled maintenance period, being carefully monitored.

In case of more serious damages, it is also not necessary to stop the whole power unit. Then, only the regeneration circuit is bypassed and operation of the other components of a unit is continued without active regeneration line due to economic reason.

3. PRESENTATION OF DEVELOPED METHOD FOR FAILURE MODE DETECTION OF FEEDWATER HEATERS

Due to the complexity of heater construction and strong nonlinear character of physical phenomena occurring there, creation of exact mathematical model of such system is computationally demanding and requires extensive field knowledge [1]. Moreover, not all parameters needed for precise object modelling are directly measured and registered by the plant monitoring system, due to low ratio of relevance to cost of such measurements. To deal with this lack of data, it is necessary to apply advanced identification techniques, e.g. 'grey box approach' [2], to retrieve missing data, increasing computational effort.

Taking all mentioned facts into consideration, it was decided to implement a simple model of heat exchanger, (Fig. 3) [3]. On the basis of a number of known operational parameters: feedwater temperature entering and leaving the heater, steam temperature and feedwater mass flow through a heater, the heat transfer coefficient of the heater is determined for every data sample.

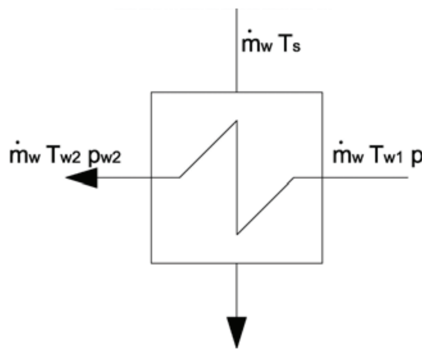


Fig. 3. Scheme of analysed heat exchanger [3]

In order to simplify the model numerous assumption considering feedwater heater must have been taken. The following facts are negligible [2]:

1. the exchange of the heat between the cavity and the external environment,
2. accumulation of the heat in the water,
3. the exchanges of the energy and the mass, caused by the surface phenomena at the interface between the condensing and the subcooling areas.

Additionally, it is assumed that:

1. all the areas where the exchange of the heat takes place are not distinguished and treated as a single chamber,
2. the pressure in the cavity is constant, uniformly distributed and equal to the steam pressure at the inlet,
3. the enthalpy is averaged over each of the areas based on the boundary conditions of each heater chamber,
4. the feedwater is in a liquid state and in a subcooling condition,
5. the pressure of the fluid in the tube-bundle equals the pressure of the feedwater at the inlet,
6. the physical properties of the tube-bundle metal are uniform, and the longitudinal heat conduction in both the pipe metal and the fluid is negligible.

Then, heat exchanger can be described with the following equation:

$$\mathrm{k} \cdot \mathrm{F} \cdot \frac{T_{w2} - T_{w1}}{\ln \frac{T_s - T_{w1}}{T_s - T_{w2}}} = \dot{m}_w \cdot c_p \cdot (T_{w2} - T_{w1}) \quad (1)$$

Detection of feedwater heater condition is based on analysis of phenomenological parameters, i.e. change of heat transfer coefficient of the heater. It is assumed that heat transfer in the heater is affected by its typical malfunctions, such as leakages. Value of heat transfer coefficient is strongly correlated with other parameters of power unit, such as its instantaneous power or steam pressure on turbine extraction (Fig 4). In steady operating conditions higher power level corresponds to higher value of heat transfer coefficient k. In transient states, i.e. during run-ups, run-downs or shut-down periods, heat transfer coefficient takes arbitrary values, due to unsteady temperature and pressure of steam and feedwater. Therefore, mentioned periods were neglected and are not taken into consideration during analysis.

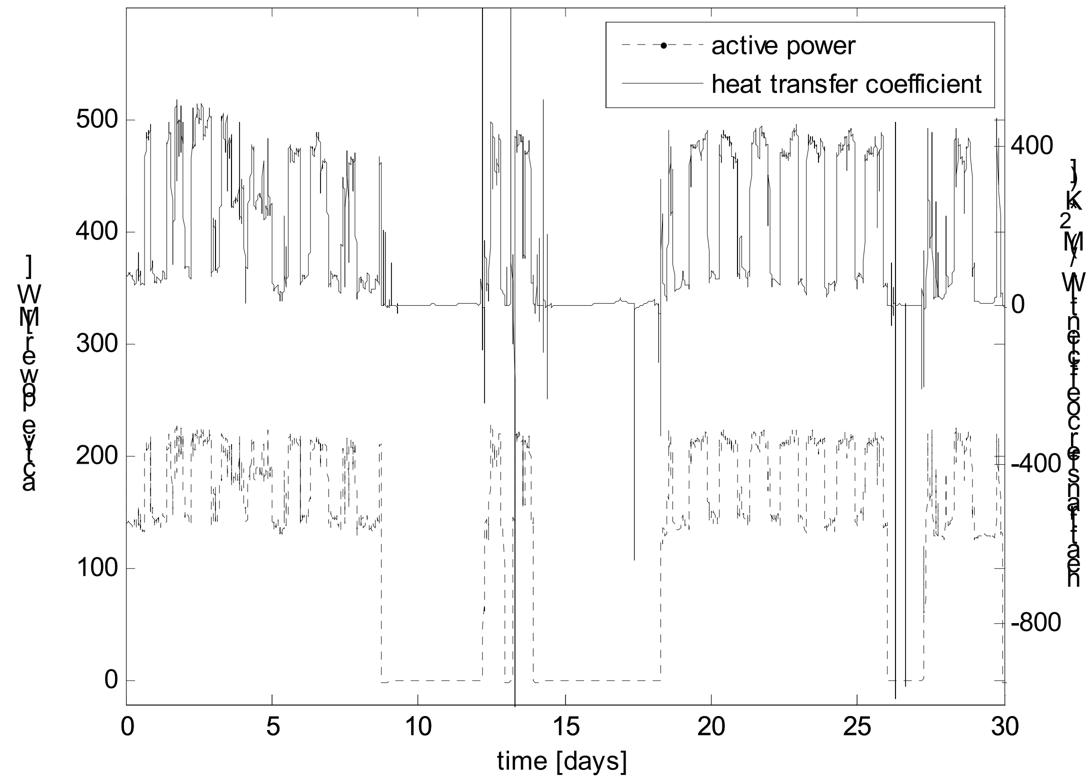


Fig. 4. Trends of heat transfer coefficient for heater XW1 and active power of the unit

A power unit frequently changes its operating point, due to fluctuating demands for electrical energy during day and night. Moreover, the heater possesses some thermal capacity and it does not heat up or cool down as fast as the generated power rate changes. Therefore, it is not that straightforward to determine if the observed change in heat transfer is caused by the power rate variation or any possible damage inside the heater.

To tackle with those problems, a method must have been proposed. There was provided the following solution: (i) application of a moving window and calculation of a mean value of heat transfer coefficient for each interval enclosed by the window, and (ii) division of operating range into a number of intervals with respect to power rate and treating them separately.

The reason for the application mentioned operations (i) is that considering historical data together with current value may reduce the influence of thermal capacity of the heater on its heat conduction parameter and provide more accurate results. The second (ii) operation is supported by the assumption that heat transfer coefficient should remain constant for long periods on condition that the same operating point is examined. Plotting calculated values basing on described procedure, it is expected to obtain several curves representing constant values. However, when malfunction of a heater occurs, those constant curves should be distorted.

4. VALIDATION OF THE METHOD ON THE BASIS OF OPERATIONAL DATA

According to previously made assumption, values of heat transfer coefficient during failure modes should vary significantly from typical values. Figure 5, which represents heat transfer coefficient versus unit power, supports this assumption.

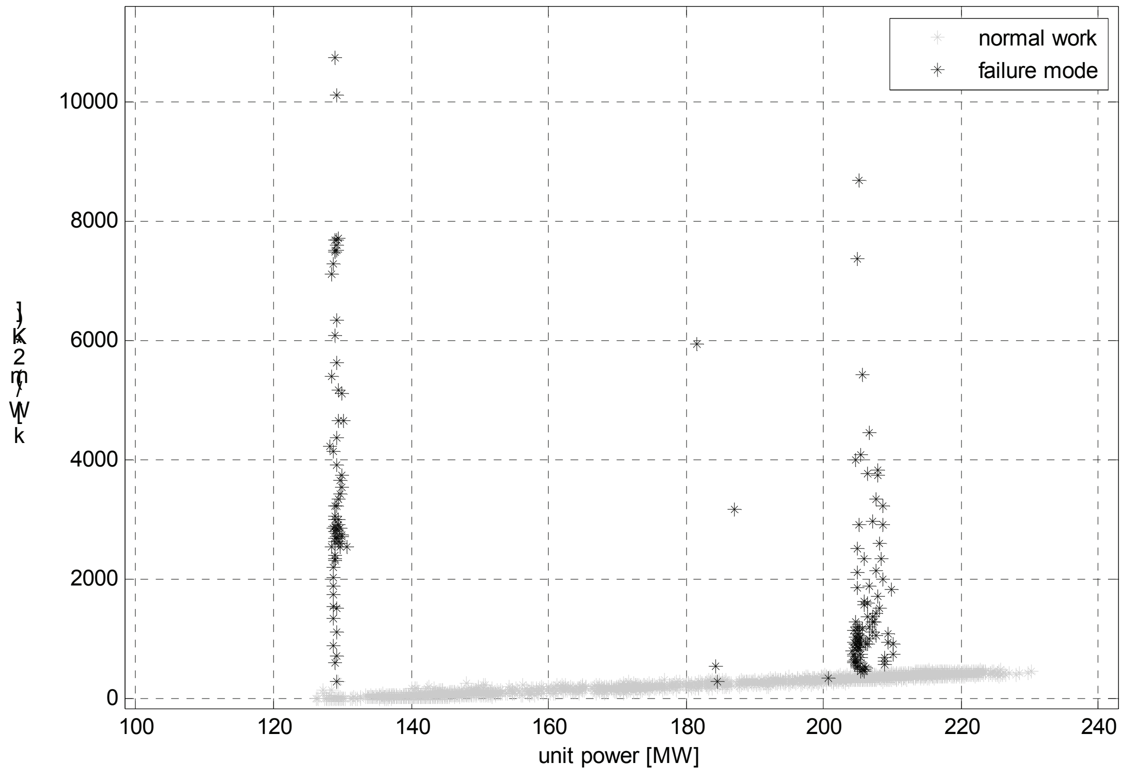


Fig. 5. Heat transfer coefficient versus unit power during normal operation and failure mode

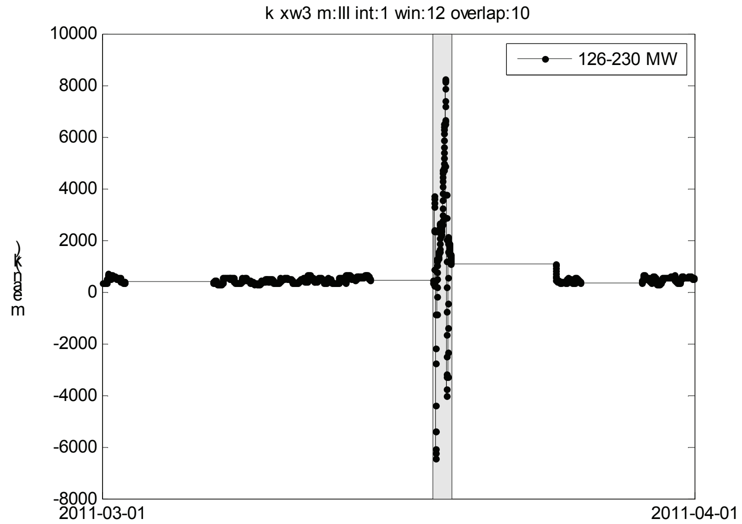
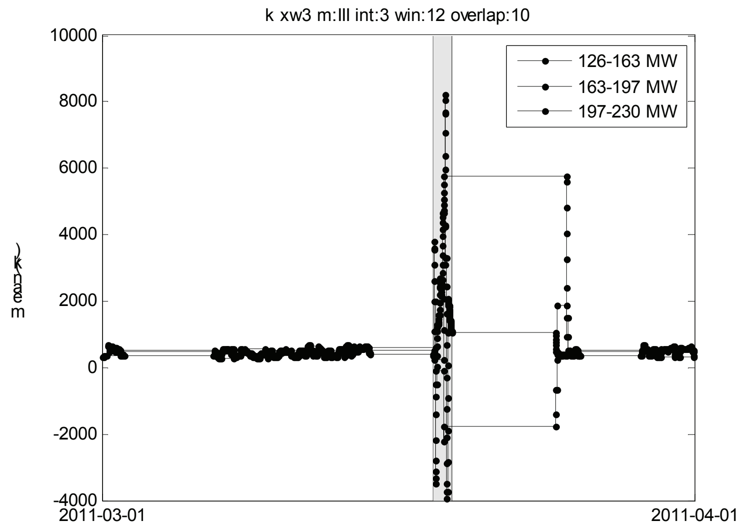
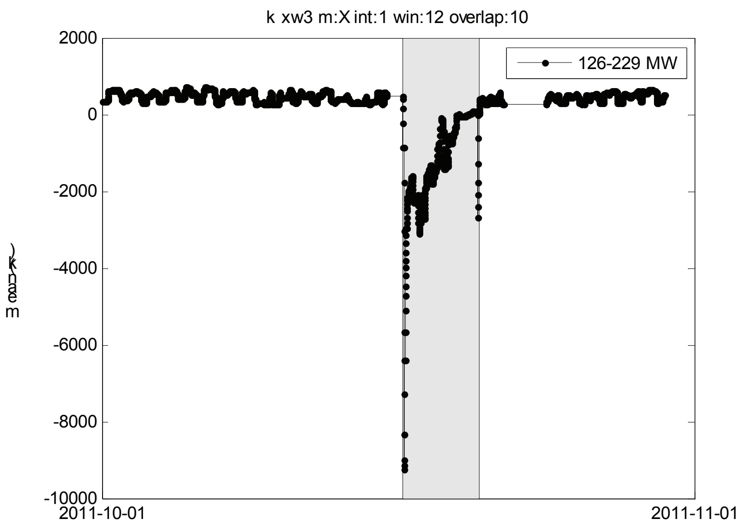
An advantage was taken from possessing real operational data from the power plant, together with specified breakdown periods. This allowed to observe changes in heat transfer trend in correlation with pre-classified malfunctions of feedwater heaters. An algorithm which produced visualisations of results for different parameters was implemented in Matlab environment. The procedure was tested for all three high-pressure feedwater heaters (Fig. 6) and for several datasets regarding different periods.

In order to find the best parameters, an experiment was designed. The scope was to find out what should be the optimal values of window length, overlap number and quantity of power rate intervals. Moreover, a choice should have been made to work either straight on consecutive values of heat transfer coefficient or use the difference between values of two following samples. In considered experiment, the objective was to enable clearest data visualisation, provide high precision and ensure early fault detection. To achieve this, several values of above-mentioned parameters were examined and, for each proposed parameter value, visualisations were made for the data considering the whole year period.

The results of experiment revealed that the maximum reasonable quantity of power rate intervals can be three, since increasing this quantity results in decreased clarity of the plots. The windows must consist of no more than 12 samples (1-hour windows), because otherwise some data may be lost due to averaging of longer period's data. Finally, an overlap number may be as large as possible, because it increases sampling rate of processed data. It was also decided to operate on consecutive values of heat transfer coefficient, instead of using the difference between values of two following samples. Although such solution requires tuning of warning thresholds for each particular case, it provides better potential for distinction between steady operation and faults.

Exemplary results are presented in Table 1. Breakdown periods corresponds to pipe leakages in heaters XW2 and XW3.

Table 1. Results of method application. Malfunction periods are denoted with shaded background

Leakage in piping system




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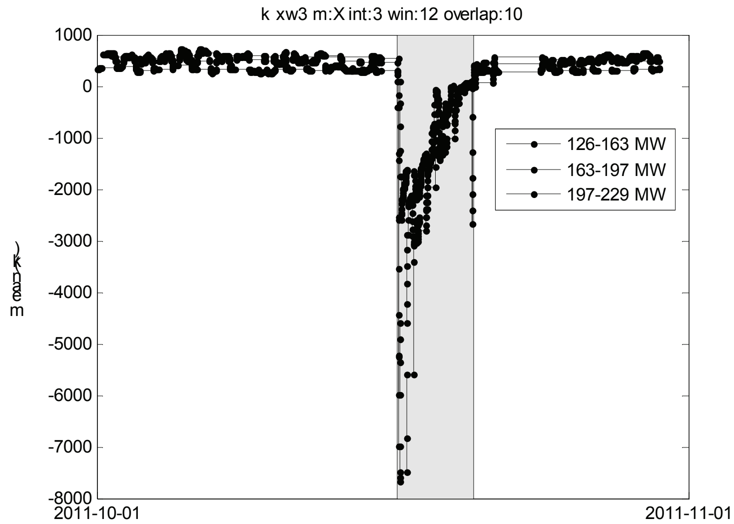
Leakage in piping system


The experiment has indicated that the idea to observe phenomenological parameter, such as heat transfer coefficient, may be applied to feedwater heater's failure mode detection. Basing on available datasets and knowledge about heaters malfunctions it has been proved that there is clear distinction between steady operation and faults visible. The accuracy of developed method depends on proper choice of parameters .

The algorithm used for determining the heat transfer coefficient may be applied to any feedwater heater system, on condition that required process parameters are measured. Since feedwater heaters have various designs resulting in different nominal heat conduction ability, it is necessary to determine operational range of heat transfer coefficient for each particular heater. Proper definition of that range enables setting warning or error thresholds, indicating heater faults.

Available data does not allow to estimate if the method is able to detect malfunctions earlier than it is possible with use of conventional methods. Each tested malfunction appeared right after the run-up of the power unit, so it was not possible to check the heater line's condition during shut-down.

It is believed that after proper tuning, the accuracy of developed method is sufficient for failure mode detection of feedwater heaters. Nevertheless, it should be marked, that all conclusions were made on the base of limited number of cases, however, some efforts are made to create a possibility of taking advantage of a larger dataset.

5. SUMMARY

A method for detection of feedwater heater failure modes described in this paper is valid in all tested operational data-based cases. It provides a simple and not computationally demanding solution for monitoring of heater operation, without the need of installing additional measurement devices in the heater line.

The parameter describing the heat transfer inside the heater is calculated as a simplified function of available measured quantities and it does not consider heater inner structure and phenomena occurring there. This may influence the accuracy of the method, however, in examined operational conditions performance of the method is sufficient. Implementation of advanced grey-box approach FPDD model of a feedwater heater will be investigated to check if it is able to improve the performance of proposed method.

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