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Real-time temperature field reconstruction of boiler drum based on fuzzy adaptive Kalman filter and order reduction

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ABSTRACT

Based on the fuzzy adaptive Kalman filter (FAKF) and an order reduction technique, a real-time on-line temperature field monitoring method for boiler drum is established. Adopting the measured temperatures of the drum outer wall, the FAKF and weighted recursive least squares algorithm (WRLSA) are used to acquire the internal heat flux and reconstruct the temperature field of a boiler drum inversely. In the above process, the aggregation method is developed to reduce the orders of the heat transfer model, by which the accurate reconstructed results can be achieved using less measurement points. In addition, using the filter residual, the process noise covariance of the Kalman filter (KF) is adjusted by fuzzy inference. Thus, the stability of the technique for temperature field reconstruction is improved. The start-up curve of a 600 MW subcritical boiler is used to verify the effectiveness of the proposed method.

1. Introduction

During operation under transient conditions of thermal systems, for example, during the rapid startups, shutdowns and load changes, there are excessive thermal stresses in thick-wall components in the conditions of high temperature and pressure (i.e. boiler drums, separators and water tanks) [1–4]. Real-time monitoring of the metal temperature distribution of this kind of components is essential to improve the safety and economy of thermal systems.

With the development of numerical calculation algorithm and computer technology, the numerical heat transfer method is widely used in the research of thermal equipment temperature and stress fields [5,6]. In practical operation, heat transfer boundary conditions of thermal equipment (especially the internal boundary conditions such as heat transfer coefficient, etc.) are difficult to be obtained exactly, which seriously undermines the simulation credibility of the temperature distribution and limits its actual application in on-line temperature monitoring.

The method of inverse heat transfer problem (IHTP) is a promising solution for the real-time monitoring of thermal equipment temperature field. Using IHTP method, the temperatures of external wall, which are easy to be acquired, can be adopted to inversely calculate the internal thermal boundary conditions and reconstruct the temperature field of thermal equipment [7–9].

Real-time inversion of internal thermal boundary conditions and online reconstruction of temperature fields for thermal equipment are typical unsteady inverse heat transfer problems. The sequential function specification method (SFSM) proposed by Beck has been widely used to solve IHTP [10,11]. Based on dynamic matrix control, Wang et al. [12,13] established a method for the simultaneous regularization inversion of the unsteady heat transfer boundary conditions. These two methods need the future measurement information of the system; therefore, they cannot be used to monitor the temperature field in real time.

With respect to the real-time method of IHTP, there were some proposed solution [14–21]. Feng et al. [16] established the transfer function of the temperature and heat flux on the front and back surfaces of a 1-dimensional slab. Then, the polynomial approximation was used to construct the inverse Laplace transform to obtain the real-time inversed results. Alifanov et al. [15] investigated the stability of solving IHTP using Kalman filter. J. Taler et al. [17,18] adopted the space marching method (SMM) to study the multidimensional unsteady inverse heat conduction problem. Moreover, he used this method to get the inner heat transfer coefficient and monitor the temperature field of the drum. Combining

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the Kalman filtering (KF) and weighted recursive least squares algorithm (WRLSA), Tuan et al. [19,20] proposed an input estimation method (IEM) to achieve real-time inversion of boundary heat flux and reconstruction of temperature field. In IEM, the KF is used to estimate states and residual sequence of the system while the WRLSA is used to get the intensity of heat source. Also, the IEM was introduced to predict the time-varying thickness of phase-change banks on the inside surface of the wall of high temperature furnaces by LeBreux [21], which is helpful for preventing the sudden and accidental loss of the protective banks.

A transfer function is used to describe the relation of a pair of input and output variables, thus the inverse Laplace transform method would be much difficult to deal with the MIMO system. When the SMM and IEM are used in thermal equipment temperature field reconstruction, the practical difficulty they faced is, whether it is SMM or IEM, that it need enough measurement information of outer wall temperatures. In principle, the SMM requires the temperature measurement information of all discrete points on the outer wall of the thermal device. Similarly, for the IEM, if the discrete state equation and KF are used directly for temperature field reconstruction, the reconstructed results will obviously deteriorate when temperature sensors cannot completely cover all the discrete grids of outer wall.

The simulation results in Refs. [20,21] showed that the inversed results using IEM were unbelievable in an initial period of time for the large oscillations. In addition, in the process of states reconstruction by KF method, the reconstructed results will likely appear obvious deviation even be unstable when the estimation of process noise covariance mismatches with the actual one seriously [22].

Based on fuzzy adaptive Kalman filter (FAKF) and order reduction techniques, a real-time on-line monitoring method for boiler drum's temperature field is established. In view of the main problems in existing methods, the aggregation method is developed to reduce the orders of the heat transfer model, which significantly make the temperature reconstruction results more independent on the number of sensors. According to the residual renewal array of the outer wall, the process noise covariance of KF is adjusted by fuzzy inference, which contributes to the stability of the temperature field reconstruction results.

The start-up curve of a 600 MW subcritical boiler is used to demonstrate the effectiveness of the proposed method.

2. Direct heat transfer problem of boiler drum

2.1. Heat transfer model of drum

Boiler drum is a thick wall cylinder with the outer wall covered by a thick layer of insulation. In a drum, the lower part (under the water level) is boiler water while the upper (above the water level) is saturated steam, as shown in Fig. 1. The following assumptions are made: 1) The wall's axial heat conduction is ignored; 2) The outer wall of the drum is insulated; 3) Material's thermal properties are constant; 4) The radiative heat transfer in the drum is not taken into account; 5) The steam and water in the drum are saturated.

Combining the simplified assumption, the governing equation, initial and boundary conditions of the drum wall in the Descartes coordinate system are as shown by following equations:

$$\frac{\rho c_p}{\lambda}\frac{\partial T(\tau,r,\varphi)}{\partial \tau}=\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T(\tau,r,\varphi)}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 T(\tau,r,\varphi)}{\partial \varphi^2} \quad r_{in}\le r\le r_{out}, 0\le\varphi<2\pi \tag{1}$$

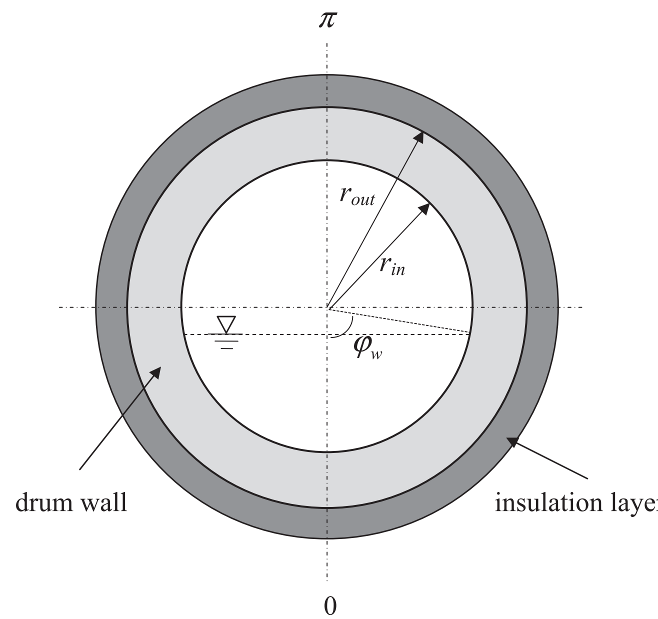

Fig. 1. Simplified physical model of boiler drum.

$$-\lambda\frac{\partial T(\tau,r,\varphi)}{\partial r}=0 \quad r=r_{out}, 0\le\varphi<2\pi \tag{2}$$

$$-\lambda\frac{\partial T(\tau,r,\varphi)}{\partial r}=h_w[T_s(\tau)-T_{in}(\tau,r,\varphi)] \quad r=r_{in}, 0<\varphi<\varphi_w \& 2\pi-\varphi_w<\varphi<2\pi \tag{3}$$

$$-\lambda\frac{\partial T(\tau,r,\varphi)}{\partial r}=h_s[T_s(\tau)-T_{in}(\tau,r,\varphi)] \quad r=r_{in}, \varphi_w<\varphi<2\pi-\varphi_w \tag{4}$$

$$T(0,r,\varphi)=T_0 \tag{5}$$

Where T is the temperature of the drum; ρ, c_p and λ are the density, heat capacity and thermal conductivity coefficient separately; T_s and T_{in} are the temperature of the steam or water and the inner wall temperature of the drum respectively; h_w and h_s are the heat transfer coefficient of water and steam with drum wall respectively; φ_w is the angle between water level and vertical direction of the drum, r_{in} and r_{out} are the inner diameter and outer diameter of the drum respectively.

2.2. Discretion of heat transfer area in drum wall

Along the radial and circumferential directions, the drum wall area are meshed into m-1 and n equal parts respectively, which results in mn space nodes as shown in Fig. 2. The radial interval Δr and the circumferential interval $\Delta\varphi$ are as follow respectively:

$$\Delta r=\frac{r_{out}-r_{in}}{m-1} \tag{6}$$

$$\Delta\varphi=\frac{2\pi}{n} \tag{7}$$

In Fig. 2, each node along the first radial layer represents a body of the peripheral thickness $\frac{\Delta r}{2}$ and a circumferential angle $\Delta\varphi$; each node in ith ($2\le i\le m-1$) layer represents a body of the peripheral thickness Δr and circumferential angle $\Delta\varphi$; each node along the