Progress in Nuclear Energy 81 (2015) 161–168

Contents lists available at ScienceDirect

Progress in Nuclear Energy

journal homepage: www.elsevier.com/locate/pnucene

A two-dimensional inverse heat conduction problem for simultaneous estimation of heat convection coefficient, fluid temperature and wall temperature on the inner wall of a pipeline

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ARTICLE INFO

Article history:
Received 13 October 2014
Received in revised form
14 January 2015
Accepted 30 January 2015
Available online

Keywords:
Thermal fatigue
Inverse heat conduction problem
Conjugate gradient method
Temperature fluctuations
Heat convection coefficient

ABSTRACT

The thermal stress caused by thermal stratification in the pipelines of nuclear plants can easily induce thermal fatigue. Predicting the temperature fluctuations at the inner wall in the pipeline without destroying the integral structure of the pipeline is one way of preventing accidents and ensuring safe operation in nuclear plants. In this work, the conjugate gradient method (CGM) is applied to solve the two-dimensional inverse heat conduction problem (IHCP) with multi-variables, in order to estimate the unknown temperature fluctuations at the inner wall of a cross profile, the temperature fluctuations of the fluid near the inner wall, and the heat convection coefficient between fluid and the inner wall of the cross profile in the pressurizer surge line, based on experimental outer wall temperature measurements. The accuracy of the inverse algorithm is then examined by comparing the estimated outer wall temperatures with the experimental temperatures. The numerical results show that the inner wall temperature of the cross profile can be accurately estimated by using the inverse algorithm for the test case considered.

1. Introduction

The inverse heat conduction problem (IHCP) has numerous important applications in estimating unknown boundary/initial conditions, or the thermophysical properties of physical models, using temperature measurements inside or outside the models. This is an interdisciplinary problem involving heat transfer theory, physics, mathematics, computer technology and experiment. Because of its effectiveness, IHCP has attracted considerable interest and has been widely applied in science and engineering. For example, Ijaz et al. (2007) estimated the time-dependent boundary heat flux in a two-dimensional heat conduction domain with heated and insulated walls; Wang et al. (2011) solved the two-dimensional steady inverse heat conduction problem in order to estimate the boundary conditions; Yang (2009) proposed a sequential method to estimate the boundary conditions of two-dimensional hyperbolic heat conduction problems; Sladek et al. (2006) solved stationary and transient heat conduction inverse problems in two- and three-dimensional axisymmetric bodies; Huang and Chen (2000) estimated the unknown boundary heat flux in a three-dimensional irregular duct flow problem; Shidfar et al. (2006) presented a numerical method for identifying the surface heat flux history in an inverse heat conduction problem with a nonlinear source term; and Volle et al. (2009) analyzed the solution of the linear, inverse, transient heat conduction problem (IHCP) for a cylindrical geometry. In addition, we have previously estimated the fluid temperature (Lu et al., 2010) and the inner wall temperature (Lu et al., 2011) in a pipeline.

Many methods are available to solve the IHCP, and they can be generally classified into two groups, stochastic and gradient-based methods. The advantage of the stochastic methods is their capability in searching for the global optimum. However, stochastic methods suffer from problems of low convergence and usually require large computational efforts. In contrast, the gradient-based methods have a fast convergence speed and high accuracy. In a gradient-based method, the determination of the sensitivity matrix

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http://dx.doi.org/10.1016/j.pnucene.2015.01.018

is essential. However, the sensitivity matrix is always difficult to calculate precisely (Cui et al., 2012). For these reasons, the conjugate gradient method (CGM), which belongs to the category of gradient-based methods, is used to solve the IHCP in this work. The CGM is based on perturbation principles and transforms the inverse problem into the solutions of three problems, namely, the direct, the sensitivity, and the adjoint problems (Lu et al., 2010). The finite element method (FEM) is a powerful tool, which can be efficiently used for static, dynamic, linear, and nonlinear engineering problems (Khajehpour et al., 2013). In order to calculate the sensitivity matrix precisely, the FEM is applied here to solve the problem directly.

Pipeline systems are widely used in nuclear power plants, oil factories, chemical plants and other fields. When hot and cold fluids mix inside the pipeline systems, thermal stratification or thermal striping can occur. The temperature fluctuations induced by thermal stratification and the thermal striping phenomena may cause cyclical thermal stress variations leading to thermal fatigue cracking of pipe walls in the pipeline systems (Bieniussa and Reck, 1999; Metzner and Wilke, 2005; Hu and Kazimi, 2006; Boros and Aszódi, 2008; Lee et al., 2009). In recent years, many accidents caused by thermal fatigue have occurred, and hence the analysis of thermal fatigue has received considerable attention. Griesbach et al. (1991) applied the EPRI FatiguePro system to address surge line stratification at the San Onofre Nuclear Generating Station, but only some temperature measurements outside the pipe were taken, and these do not allow a comprehensive analysis of thermal fatigue. Some other researchers have made use of CFD to simulate the temperature field in pipeline systems (Kim et al., 1993; Hu and Kazimi, 2006; Kamide et al., 2009; Lee et al., 2009; Lu et al., 2013). However, such numerical studies are very expensive, requiring considerable computing time. IHCP has many advantages, especially for analysis of thermal fatigue in a nuclear plant, where the requirements of structural integrity are very strict. Therefore, the estimation of heat convection coefficient, fluid temperature and wall temperature on the inner walls using IHCP is presented in this work.

2. Mathematical model

Fig. 1 shows the pressurizer surge line in the experimental flow. Because the experimental data only involve the temperature at some measurement points on the outer wall—as is the situation in a nuclear power plant—this problem can be regarded as a two-dimensional transient inverse heat conduction problem with multi-variables, requiring simultaneous estimation of heat convection coefficient, fluid temperature and wall temperature on the inner wall. The thought for solving the IHCP is modeled on a paper (Zhu et al., 2011). In order to examine the effectiveness of the IHCP proposed in the work, the cross profile 22D is chosen. 22D locates in the corner of the pipeline, where the fluid flow condition can easily change. Because the pressurizer surge line has a constant diameter, the same physical model, with different internal fluid temperature and outer wall temperature information, can be applied to any cross profile. Hence, if our proposed method can be confirmed to be effective for this cross profile, it can be applied to any other cross profile.

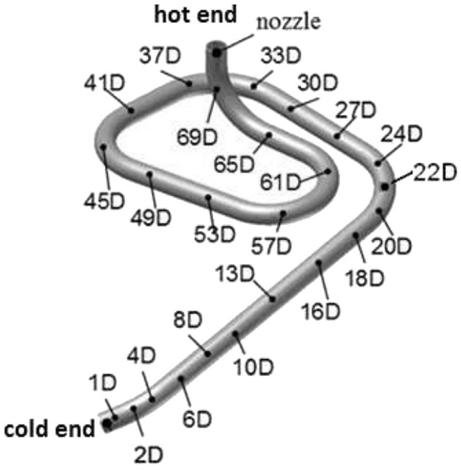

Fig. 1. Pressurizer surge line.

Fig. 2 shows the physical model used in our work. The pipe is made of stainless steel with an outer diameter of 65 mm, inner diameter of 56 mm, and heat conductivity coefficient $\lambda = 19.35\mathrm{W}/(\mathrm{m}\cdot\mathrm{K})$. The inner wall is subjected to the convection boundary condition, where the heat convection coefficient is unknown; the outer wall is subjected to the heat insulation condition, $q = 0$, and the fluid temperature inside the pipeline changes over time, and it is unknown; the time step is $\Delta\tau = 1\mathrm{s}$, and the total time is 300 s.

The governing equations and corresponding boundary conditions for the transient direct heat conduction problem (DHCP) are:

$$\frac{\partial T}{\partial \tau} = \alpha\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \quad (x,y)\in\Omega \tag{1}$$

$$-\lambda\left(\frac{\partial T}{\partial n}\right)_{\mathrm{w}} = h_{\mathrm{f,in}}\left(T_{\mathrm{f,in}} - T_{\mathrm{w}}\right) \quad (x,y)\in\mathrm{InnerWall} \tag{2}$$

$$-\lambda\left(\frac{\partial T}{\partial n}\right)_{\mathrm{w}} = q \quad (x,y)\in\mathrm{OuterWall} \tag{3}$$

where T is the temperature of the solid area;α is the thermal diffusivity of the pipe; x, y and τ are the space and time variables; λ is the thermal conductivity of the pipe, n is the direction vector normal to the boundary wall; $h_{\mathrm{f,in}}$ is the convection heat transfer coefficient on the inner wall; $T_{\mathrm{f,in}}$ is the fluid temperature near the inner wall; T_{w} is the temperature of the inner wall; q is the heat flux on the outer wall.

This is a problem that utilizes the known temperatures at measurement points on the outer wall to estimate the heat convection coefficient, fluid temperature and wall temperature on the inner wall. This inverse problem can be mathematically transformed into an optimization problem as follows:

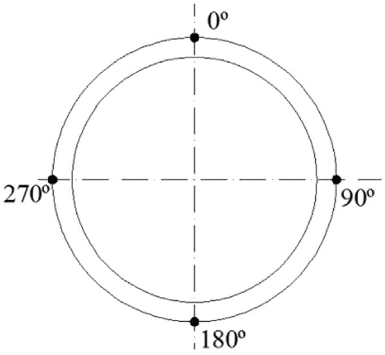

Fig. 2. Physical model.