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Fuzzy estimation for unknown boundary shape of fluid-solid conjugate heat transfer problem

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ABSTRACT

This study proposed a decentralized fuzzy inference method (DFIM) for estimating the unknown boundary shape of a fluid-solid conjugate heat transfer (CHT) system. The method coupled boundary element method (BEM) with finite volume method (FVM) is applied to solve the direct problem. A set of decentralized fuzzy inference units is established. The deviations between the calculated and measured temperatures are taken as the input parameters of fuzzy inference units, and obtain the corresponding inference components by fuzzy inference. Then a synthesizing weighted approach based on normal distribution and with geometry factor is built to weight and synthesize the inference components, and gain the compensations of the boundary shape to revise the guess values of unknown boundary configurations. Some numerical experiments are performed to discuss the validity of the present approach by using different initial guesses of unknown boundary shape, the number of measuring points, measurement errors, etc. Comparisons with the conjugate gradient method (CGM) and genetic algorithm (GA) are also conducted.

1. Introduction

The inverse heat transfer problems (IHTPs) is to use the temperature information inside or on the surface of the heat transfer system to estimate the unknown characteristic parameters, such as thermal physical parameters [1], geometry configurations [2], boundary conditions [3], the source term [4], etc.

The inverse geometry problem has broad applications in engineering field such as non-destructive detection, geometry optimization and biological lesion detection, etc. Su et al. [5,6] applied the concept of virtual area and the linear least-squares error method to identify the geometry of inner wall of furnace, and discussed the effects of the measurement errors, number of sensors on inversion results. Huang and Chen [7] used the Levenberg–Marquardt method (L-MM) to determine the optimal design of the non-uniform fin heights and widths of an impingement heat sink module. Fan et al. [8] estimated the pipeline's inner irregular boundary based on thermal graphic temperature measurement by conjugate gradient method (CGM). Partridge and Wrobel [9] applied the genetic algorithm (GA) to estimate the size and location of a skin tumor based on the temperature information on the skin surface.

Many researches have been found in the estimation for boundary condition and thermal physical property parameter involving fluid-solid conjugate heat transfer (CHT). Chen et al. [10] estimated the unknown heat flux and temperature on the external surface of a circular pipe by using the method of rearranging the matrix forms of the governing differential equations and combining the reverse matrix method and the linear least-squares-error method. Chen et al. [11] applied the CGM to inverse the transient heat transfer rate on the external wall of forced convection pipe. Lin et al. [12] estimated the heat flux of unsteady conjugated forced convection in parallel plate channels. Zueco and Alhama [13] employed an inverse technique by combining the sequential function specification method (SFSM) and the network simulation method (NSM) to evaluate the thermal conductivity and heat capacity for a fluid flowing through a circular duct. Chen and Hsu [14] predicted the average heat transfer coefficient and fin efficiency on a vertical annular circular fin of finned-tube heat exchangers.

However, the research in geometry estimation for fluid-solid CHT problem is still very limited in the literature. Chen and Yang [15, 16] applied CGM to estimate the unknown irregular fouling

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profiles on the inner tube wall of heat exchanger and the irregular frost-layer boundary profile on the outer wall of pipe. The results indicate that the CGM can achieve good inversion result, but it needs to re-mesh the heat transfer region in the inversion process, and the effect of reducing the number of measuring points is not discussed.

Inverse heat transfer problem is usually ill-posed, which means the three conditions: the existence, uniqueness and stability of solution cannot be met at the same time [17]. Because of the ill-posedness, the estimation results by using the classical inversion algorithm, such as CGM and L-MM, would deteriorate significantly when the number of measuring points reduce or the measured temperature data contain errors [18,19]. In recent years, a lot of new inverse method have been proposed, such as GA, particle swarm optimization (PSO) and so on. Lin et al. [20] has applied the sequential method and the concept of future time to estimate the unknown temperature boundary condition of irregular shape of gas tank.

Fuzzy inference was based on the fuzzy theory, which has a strong capacity of resisting disturbance to input information, good robustness and fault tolerance to the reasoning process, and can effectively utilize the imprecise, uncertain and incomplete information to infer and make strategic decisions. These characteristics of fuzzy inference can provide new ideas and methods for overcoming the ill-posed nature of inverse problems including IHTPs. Wang et al. [21–23] has developed a decentralized fuzzy inference method (DFIM) based on fuzzy inference, which estimates the unknown boundary condition by fuzzy inference. The researches show that this method has obvious better anti-ill-posed in comparison to other inverse algorithms, such as CGM, L-MM and GA. It can effectively reduce the impact of the number of measuring points and measurement errors on inversion results.

The present paper take a circular pipe system as the example to study the fuzzy estimation for the boundary geometry of fluid-solid CHT problem. The BEM and finite volume method (FVM) are respectively used to solve direct problem in solid and fluid region. This can avoid re-meshing in solid region during inversion process compared with the method of FDM, FEM and so on. A set of fuzzy inference units is constructed for the inversion of the boundary configurations. The deviation values between the calculated and measured temperatures are used to produce the corresponding fuzzy inference component by fuzzy inference. Then a synthesizing weighted approach based on normal distribution and with geometry factor is built to weight and synthesize the inference components according to the importance of the measured information, and gain the compensations of the boundary shape to revise the guess values of unknown boundary configurations.

Compared with CGM and GA, some numerical tests are presented to discuss the effect of different initial guesses of unknown boundary shape, the number of measuring points and measurement errors on the boundary shape inversion involving fluid-solid CHT.

2. Direct problem of fluid-solid conjugate heat transfer

Fig. 1 shows a circular pipe model involving CHT. The pipe is length of L, and with the inner and outer radii R_1 and R_2. The fluid in the pipe is considered in the state of fully developed flow with constant inlet temperature T_{in} and average velocity U_f. On the outer wall of circular tube, there exists a solid adhesive layer. The following assumptions are made for the pipe system:

(1) The adhesive layer is symmetric to the center line of pipe and the outer surface of the adhesive layer experiences convective heat transfer with the external environment;
(2) The circular pipe wall and the solid adhesive layer are homogeneous with constant thermal conductivity and there is no thermal contact resistance between the two interfaces;
(3) The two ends of the circular tube and the adhesive layer are taken as adiabatic.

The pipe region Ω_p and the adhesive region Ω_a both contains four boundaries, which are $(\Gamma_p^1, \Gamma_p^2, \Gamma^{12}, \Gamma_p^4)$ and $(\Gamma^{12}, \Gamma_a^2, \Gamma_a^3, \Gamma_a^4)$, and they have the common boundary Γ^{12}.

2.1. Solid region

The steady-state heat conduction equation and boundary conditions of two regions are:

$$\frac{\partial^2 T_p(x,r)}{\partial r^2} + \frac{1}{r}\frac{\partial T_p}{\partial r} + \frac{\partial^2 T_p(x,r)}{\partial x^2} = 0 \tag{1}$$

$$\frac{\partial^2 T_a(x,r)}{\partial r^2} + \frac{1}{r}\frac{\partial T_a}{\partial r} + \frac{\partial^2 T_a(x,r)}{\partial x^2} = 0 \tag{2}$$

$$T_p(x,r) = T_a(x,r) \quad 0<x<L, r = R_2 \tag{3a}$$

$$k_p\frac{\partial T_p(x,r)}{\partial r} = k_a\frac{\partial T_a(x,r)}{\partial r} \quad 0<x<L, r = R_2 \tag{3b}$$

$$\frac{\partial T_p(x,r)}{\partial x} = 0 \quad x = 0 \ \ or \ \ x = L, R_1 < r < R_2 \tag{3c}$$

$$\frac{\partial T_a(x,r)}{\partial x} = 0 \quad x = 0 \ \ or \ \ x = L, R_2 < r < R_{out}(x) \tag{3d}$$

$$-k_a\frac{\partial T_a(x,r)}{\partial n} = h\left(T_{R_{out}(x)} - T_\infty\right) \quad 0<x<L, r = R_{out}(x) \tag{3e}$$

where T_p and T_a are the temperature of pipe wall region and solid adhesive layer region, respectively; T_∞ is the environment temperature; h is the convective heat-transfer coefficient; k_p,k_a are the thermal conductivity and $R_{out}(x)$ is the outer wall radius distribution of adhesive layer.

The BEM is used to solve the heat conduction in solid area. For the adhesive layer region Ω_a, the boundary $\Gamma_a = \Gamma^{12} \cup \Gamma_a^2 \cup \Gamma_a^3 \cup \Gamma_a^4$ is discretized with constant boundary element and get $M_a = M_a^{12} + M_a^2 + M_a^3 + M_a^4$ boundary elements $\Gamma_j (j = 1,2,\ldots,M_a)$. At the midpoint of the boundary element is the boundary node, and the temperature and heat flux at the node is constant and equal to the value on the boundary element. Then we get the discretization equation of Eq. (2):

$$\sum_{j=1}^{M_a} H_{i,j}T_j = \sum_{j=1}^{M_a} G_{i,j}q_j \quad (i = 1,2,\ldots,M_a; j = 1,2,\ldots,M_a) \tag{4}$$

where T_j is the temperature at the node j and $q_j = \partial T_j/\partial n$ is the normal derivative of T_j; $H_{i,j}$ and $G_{i,j}$ are the geometry coefficients which relate to the distance between the node i and node j.

When $i \neq j$ [24]: