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Monitoring of wall temperature fluctuations for thermal fatigue in a horizontal mixing T-junction pipe

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ABSTRACT

Turbulent penetration and unsteady thermal stratification can occur when hot and cold fluids mix in T-junction pipes at nuclear plants. Temperature fluctuations with large amplitude and high frequency caused by the unstable thermal stratification can lead to time-varying thermal stress and even induce thermal fatigue of T-junction pipes. Monitoring of wall temperature fluctuations of T-junction pipes at nuclear plants has received considerable interest because the thermal fatigue failure of these pipes could present severe environmental implications and large economic losses. In this study, mock-up tests and analyses were conducted to develop a monitoring program for monitoring the wall temperature fluctuations of mixing T-junction pipes. Using a test loop, we simulated the mixing flow of hot and cold fluids in a horizontal T-junction pipe at a nuclear plant. To monitor the wall temperature fluctuations of the horizontal T-junction pipe, we developed a program in MATLAB. The monitoring program could filter out unwanted noise from raw measured temperature data by the singular spectrum analysis and guarantee a grid-independent and time-step-independent solution. With high accuracy and computational efficiency, the monitoring program was able to monitor the wall temperature fluctuations of a horizontal mixing T-junction pipe by measuring temperatures on the outer wall.

1. Introduction

Turbulent penetration and unsteady thermal stratification can occur when hot and cold fluids mix in a T-junction pipe at nuclear plants. Temperature fluctuations with large amplitude and high frequency caused by the unstable thermal stratification can lead to time-varying thermal stress and even induce thermal fatigue on the inner wall (Lu et al., 2010). Fatigue cracks have been found in mixing T-junction pipes at nuclear plants (Chapuliot et al., 2005). The monitoring of thermal fatigue at nuclear plants becomes more and more currently performed, mainly on pipe system the failure of which could have severe effects on the environment. The easiest way of performing this monitoring is to estimate thermal stress at the points of interest from measured inner wall temperatures. However, in order to maintain integrity of nuclear power pipe system, numerous cases exist where the inner wall temperatures are not available and only an outer wall temperature measurement is feasible. In these cases, it is very useful to solve an IHCP to evaluate damage of thermal fatigue from measured temperatures on the outer wall.

Applications of IHCP are often found in these engineering problems in which direct measurements in a body are difficult to obtain wanted thermal quantities such as follows: **(1) inner wall temperature** (A two-dimensional IHCP was solved to estimate inner wall temperature of a pressurizer surge line based on outer wall temperature measurement (Lu et al., 2015). A three-dimensional IHCP was solved to estimate inner wall temperature of a pipe elbow from outer wall temperature measurement (Lu et al., 2011)); **(2) heat flux** (Multi-parameters of boundary heat flux were simultaneously recovered by solving transient nonlinear IHCPs (Cui et al., 2016). A real-time solution for a two-dimensional IHCP was presented to estimate heat flux using temperature measurement data (Najafi et al., 2015)); **(3) heat source** (An IHCP was solved to identify the radiative source term from the measured final noisy temperature (Zhang et al., 2015). A modified polynomial expansion method was developed to solve an IHCP of identifying the time dependent heat source (Kuo et al., 2016)); **(4) thermal conductivity** (Thermal contact conductivity and contact failures were estimated by solving an IHCP with the Reciprocity Functional approach from the temperatures at the lateral and lower surface of the sample (Abreu et al., 2016). The estimation of thermal conductivity was done by an IHCP knowing the heating curves at selected points of the medium

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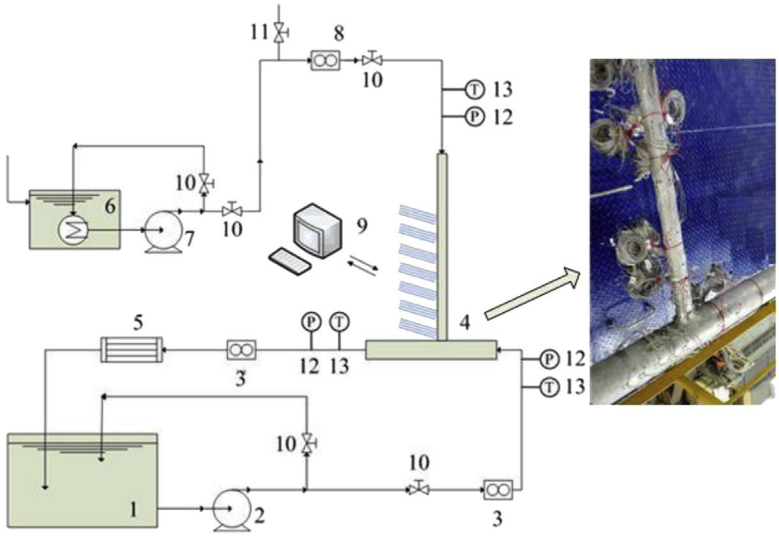

Fig. 1. Schematic diagram of the test loop. 1. Cold water tank 2. Cold water pump 3. Mass flow meter 4. Test sample 5. Heat exchanger 6. Hot water tank. 7. Hot water pump 8. High precision mass flow meter 9. Thermocouples and data acquisition unit 10. Valve. 11. Exhaust valve 12. Pressure gauge 13. Thermometer.

Table 1
Test conditions.

	Main pipe	Branch pipe
Fluid temperature in the inlet [°C]	110	200
Mass flow rate in the inlet [t/h]	506	0.19
Pressure in the inlet [MPa]	2.54	2.46

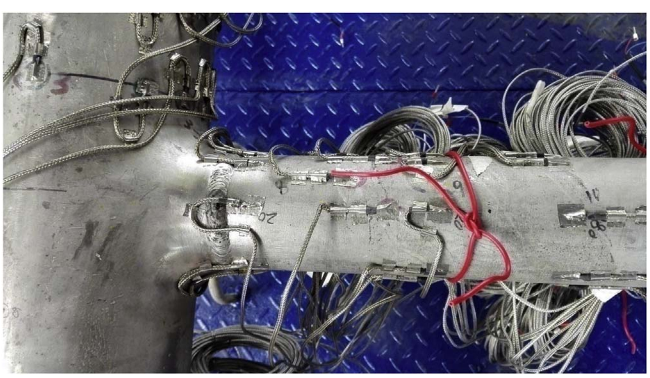

Fig. 2. Sheathed thermocouples installed on the outer wall.

(Mansour et al., 2016)); **and (5) heat transfer coefficient** (An inverse analysis approach was applied to experimental infrared temperature data with the aim of estimating the local convective heat transfer coefficient for forced convection flow in coiled pipe having corrugated wall (Bozzoli et al., 2016). A solution strategy of the IHCP was applied to estimate the local heat transfer coefficient on the inner wall of a pipe under a forced convection (Cattani et al., 2015)).

With wide applications of IHCP, a variety of numerical techniques have been proposed for the solution of IHCPs such as follows: **(1) Levenberg-Marquardt method (LMM)** (An IHCP was solved to identify the thermophysical properties of the soil by LMM (Mansour et al., 2016). An IHCP was solved to determine the optimal geometry of filler shape between two conductive bodies in a two-dimensional multiple region domains by LMM (Huang and Hsu, 2015)); **(2) least-squares method (LSM)** (Adopting the idea of the weighted LSM, we formulated an inverse problem of textile thickness-heat conductivity-porosity determination (IPT (THP) D) into a function minimization problem (Xu and Cui, 2016). Temperature dependent thermal diffusivities of two alloys were determined using a one-dimensional inverse method by LSM (Zhang et al., 2016));**(3) conjugate gradient method (CGM)** (An IHCP was solved by CGM to identify the heat losses at the jaws of a tensile testing machine (Bouache et al., 2015). An IHCP was solved by CGM to estimate the time-dependent heat flux using temperature distribution at a point in a three-layer system (Mohammadiun, 2016)); **(4) genetic algorithm (GA)** (An IHCP was solved by GA to identify the conductive and radiative parameters of a semitransparent sample (Braiek et al., 2016). An IHCP was solved by GA to determine thermal conductivity in lumber (Zhao et al., 2016)) **and (5) steepest descent method (SDM)** (An IHCP was solved by SDM to identify the boundary of unknown inclusions inside an object by applying a heat source and measuring the induced temperature near the boundary of the sample (Cimrák, 2011). A solution of an IHCP by SDM was carried out in order to determine the waste heat flux from a helicon plasma discharge using transient surface temperature measurements obtained from infrared thermography (Mulcahy et al., 2009)).

SDM, which has great potential in solving IHCP, transforms an inverse problem to a solution of three problems, namely, the direct problem, the sensitivity problem, and the adjoint problem (Huang et al., 2003). Although SDM has great potential in solving IHCP, its validity in solving IHCP in a horizontal mixing T-junction pipe has never been examined. In addition, as a numerical solution method, grid independent verification and time step independent verification should be conducted when an IHCP is solved. In existing literatures, however, grid independent verification and time step independent verification are not conducted or not conducted automatically.

In this paper, an IHCP was investigated by SDM on cross sections of main and branch pipes of a horizontal mixing T-junction to estimate wall temperature fluctuations from measured temperatures on the outer wall. Based on the IHCP, a monitoring program was developed in Matlab. With grid independent verification and time step independent verification added into it, the monitoring program could guarantee a grid-independent and time-step-independent solution. In addition, the monitoring program was validated using other measured temperatures on the outer wall.

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