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Transient inverse heat conduction problem of quenching a hollow cylinder by one row of water jets

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ABSTRACT

In this study, a two-dimensional linear transition *inverse heat conduction problem* (IHCP) was solved using the *Generalized Minimal Residual Method* (GMRES) in quenching process by water jets. The inverse solution method was validated by set of artificial data and solution sensitivity analysis was done on data noise level, regularization parameter, cell size, etc. An experimental study has been carried out on quenching a rotary hollow cylinder by one row of subcooled water jets. The inverse solution approach enabled prediction of surface temperature and heat flux distribution of test specimen in the quenching experiments by using measured internal specimen temperature. Three different boiling curves were defined in the quenching process of a rotary cylinder. Result obtained by the inverse solution showed clear footprint of rotation in surface temperature and heat flux on each revolution of cylinder and temperature variation damping from quenching surface toward interior of specimen.

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1. Introduction

There is continuous industrial demand for more advanced thermal management methods as a way to stay competitive. As a consequence, there is an increasing need for better understanding, prediction and control of the transient thermal responses and temperature distributions in many industrial and material applications [1,2]. In the steel industry, for example, improved heating and cooling techniques associated with steel quenching and annealing is desired to make production more effective, to improve quality, repeatability and material performance, and to reduce the use of expensive alloy materials and thus cost.

Quenching can be achieved by several methods, but the use of liquid water impinging jets is one of the most effective techniques used in industry. During such a process, water jets are directed towards the surface of the material to be quenched. Depending on e.g. water velocity and surface temperature, different boiling regimes occur at the interface between metal surface and impinging jet(s) [3]. This in turn affects surface heat flux and thereby the entire spatio-temporal temperature distribution and thus the quenching process.

There are many parameters affecting surface temperature and heat flux during quenching by impinging water jet(s). Several studies have investigated the effect by, e.g., the jets Reynolds number [4], water subcooling [5,6], rotation- and movement speed of the test specimen [6,4] and different size and configuration of the water jets [7–9] on the surface boiling curve. In a recent study, effect of jet-to-jet spacing, initial quenching temperature and several other parameters were investigated on cooling rate of quenching a rotary cylinder [10]. In practice it is very difficult to accurately measure the temperature and heat flux of the surface during a quenching process as the measurement device since its application disturbs the heat flux and cooling process, or cannot withstand the harsh conditions during quenching. Remote temperature monitoring by IR camera techniques is not an alternative either, as the surface wetting and boiling would seriously disturb the measurement in the wetted region. Altogether, the vast number of parameters that affects the cooling process together with the difficulty of determining surface temperature and heat flux distributions makes impinging jet quenching far from fully understood. There is a need for new and improved methods and techniques for both measurement and analysis of measurement results.

One way to circumvent some of the surface measurement problems, which is investigated in this study, is to apply an inverse problem technique to *determine* the surface temperature and heat flux based on temperature measurements beneath the surface (instead of direct measurement). By using an inverse method,

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temperature measured below the surface is used to solve a boundary value problem for the heat conduction equation [11–15]. This situation is often modeled as a *Cauchy problem* [16,17,11,18] where both temperature and heat-flux data are specified at a distance from the surface.

The Cauchy problem for the heat conduction equation is well known to be *ill-posed* [19,11,20]. This means that small measurement errors in the data may seriously disturb and even destroy the numerical solution. The ill-posed aspect has to be taken care of, which for example can be accomplished by methods that stabilize the numerical computations. Several such stabilizing methods have been proposed. One example is to reformulate the Cauchy problem for the heat conduction equation as an operator equation $Kf = g$, where $f(x,t)$ is the surface temperature and $g(x,t)$ is the interior temperature measured by the measurement device, see e.g. [21,22]. The new operator equation can subsequently be solved by using the generalized minimal residual method (GMRES) which has been shown to produce good solutions when applied to ill-posed problems [23].

In this study, the inverse heat conduction problem of an insulated quenching system including multiple water jets is solved in order to predict the surface temperature and heat flux of the test object during the quenching process. Towards this aim, the direct and inverse problems are described, and a linear operator is defined in the Arnoldi method to solve the inverse problem. An experimental setup is presented as an application of the inverse solution and a mathematical model is defined to reformulate the problem to well-posed to make it possible to use the linear operator to solve the inverse problem.

2. The direct and inverse problems

The spatio-temporal surface temperature and heat flux are the outgoing result of inverse solution by applying known measured interior temperature of test specimen into the inverse problem. In order to solve the problem, the first step is to define the *forward problem*, i.e., construct a functional relation between an assumed temperature distribution at the surface and compute the corresponding temperatures at the measurement locations by a numerical simulation. Such a model is useful both for creating test problems (which is carried out below) that allows an investigation of the theoretical properties of the problem, and also to serve as a basis for the algorithm developed for solving the *inverse problem*, i.e., finding the unknown surface temperature outgoing from temperature history carried out experimentally below the surface. The temperature inside the material is governed by the time dependent heat conduction equation, i.e.,

$$\nabla \cdot (k \nabla T) = \rho c_p T_t, \tag{2.1}$$

where k is the thermal conductivity, ρ is the density and c_p is the specific heat capacity of the test specimen's material. The computational domain is illustrated in Fig. 1 and is expressed in terms of the radius r, the axial length x, and the time t. The outer surface of the cylinder is located at radius $r = R_3$ and the inner radius is located at $r = R_0$. The measurement sensors are mounted inside the material at radii $r = R_1$ and $r = R_2$. It should be noted that in this section the measured data at radius $r = R_1$ is not used. Furthermore, a finite portion of the hollow cylinder along the x-axis for a finite period of time is considered in the inverse solution.

In order to simplify the notation, the domain is introduced as follows,

$$\Omega = \{(x,t) | L_1 < x < L_2, \text{ and } 0 \leqslant t \leqslant t_{final}\}, \tag{2.2}$$

where L_1 and L_2 represent length of the test specimen and t_{final} is the duration of temperature recording in time. Using this notation, the surface temperature $f(x,t) = T(x,t,R_3)$ is a function defined on the domain $(x,t) \in \Omega$.

In order to make the description complete, initial and boundary conditions need to be defined. On the sides of the model, i.e., for $x = L_1$ and $x = L_2$, it is assumed that $T_x = 0$, i.e., that the sides are thermally insulated. This can be seen as a symmetry boundary condition on the behavior of $T(x,t,r)$ outside the segment $L_1 < x < L_2$. The interior surface of the hollow cylinder is assumed to be a thermally insulated boundary, i.e., $T_r(x,t,R_0) = 0$.

A fair assumption of the initial condition for the test specimen's temperature, i.e., for $T(x,0,r)$, is more complicated than geometry boundary conditions because initial condition assumption has significant effects on predicted results. One possibility is to consider the initial temperature of the test specimen to be at steady state condition, i.e., the function $\widetilde{T}(x,r) = T(x,0,r)$ satisfies the equation $\nabla \cdot (k \nabla \widetilde{T}) = 0$ for $(x,y) \in \Omega$. Another alternative is that test specimen is assumed to have a constant initial temperature before quenching which is a fairer assumption for quenching applications and is considered in the present case.

2.1. The linear operator equation

As mentioned above it is assumed that the test specimen is initially at a constant temperature. The mathematical model is then as follows: Find $T := T(x,t,r) \in C^2(\Omega \times (R_0,R_3)) \cap C^1(\bar{\Omega} \times [R_0,R_3])$ such that

$$\begin{cases} (kT_x)_x + \frac{1}{r}(rkT_r)_r = \rho c_p T_t, & \text{in } \Omega \times (R_0,R_3), \\ T(x,t,r) = f(x,t), & \text{on } \Omega \times \{R_3\}, \\ kT_r(x,t,r) = 0, & \text{on } \Omega \times \{R_0\}, \\ T_x(x,t,r) = 0, & \text{for } x = L_1 \text{ ; and } x = L_2, \\ T(x,0,r) = f(x,0), & \text{on } (L_1,L_2) \times (R_0,R_3) \times \{0\}, \end{cases} \tag{2.3}$$

where $f(x,0)$ is a constant function in time.

In order to formally define the operator mapping the surface temperature onto the measurement locations, the function space is introduced

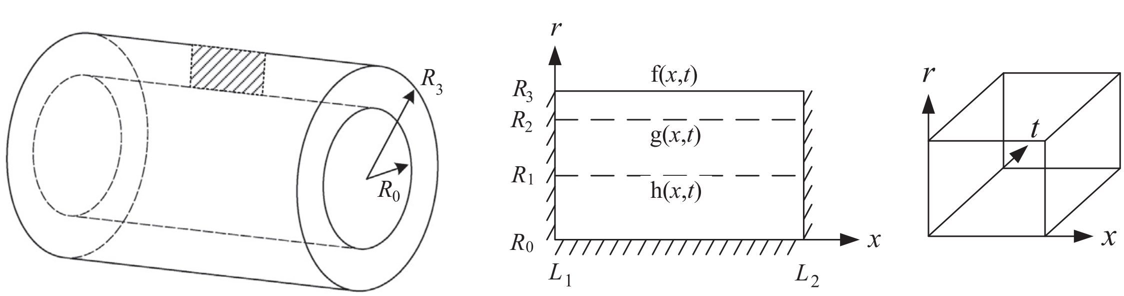

Fig. 1. Computational domain illustration.

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