Effect of Subsurface Thermocouple Installation on the Discrepancy of the Measured Thermal History and Predicted Surface Heat Flux during a Quench Operation

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Water quenching plays an important role in metallurgical and materials manufacturing operations to control both the temperature of the product during processing and its final microstructure. In order to control a water-quench process, the surface heat-transfer coefficient or heat flux must be quantified accurately. A common procedure to do this is to use an inverse heat conduction (IHC) model to estimate the heat-transfer boundary condition (heat flux or heat-transfer coefficient) based on the measured thermal history during the quench operation at a known interior location in the sample. Traditionally, thermocouples (TCs) have been extensively used during quench tests to measure the sample temperature history. This article will examine the effect of the hole used to insert the thermocouple into the sample and its orientation with respect to the quenched surface, on the perturbation in the thermal field around the TC measurement point during water-quench operations characterized by boiling heat transfer. The effect of some other factors on the perturbation of the thermal field at the TC measurement point during water-quench operations such as the diameter of the thermocouple hole, thermocouple distance from the quench surface, sample thermal conductivity, and quench intensity were also investigated. A two-dimensional (2-D) axisymmetric IHC model developed at the University of British Columbia is used to estimate the error in the predicted heat fluxes based on the thermal history measured at the thermocouple measurement point. The study showed, for some quench conditions, that the thermocouple hole must be included in the IHC analysis as an independent body with its own thermophysical and geometrical characteristics. Validation of these model-predicted results was done using water-quench experiments performed on samples of steel and aluminum plates at the University of British Columbia. Using the Biot number (Bi), a simple criterion is developed to determine when the TC hole needs to be included in the heat-transfer analysis.

I. INTRODUCTION

Increasingly, computational modeling of industrial metallurgical and materials manufacturing processes is becoming an integral part of enhancing final product quality. The modeling, design, and control of many of these operations hinges, in part, on being able to accurately quantify the heat transfer occurring at the boundary of the products being processed. In many cases, water is used as the medium to cool these components to the desired temperatures before further processing occurs. Quantification of the heat-transfer boundary conditions in these situations can be quite challenging, especially as rapid nonlinear changes in the heat flux or heat-transfer coefficient occur with the variation of the component surface temperature. Moreover, the boundary condition can also change dramatically depending on the properties of the water, the conditions under which the water is applied to the surface of the component, and the interaction of the water with the surface of the component. In light of the need for quantification of the boiling water heat transfer during the quench process and the challenges associated with this, researchers are increasingly turning to inverse heat conduction (IHC) methods to quantify surface heat fluxes based on experimental data. In these methods, the boundary heat flux is not initially known but is calculated based on accurate knowledge of the temperature-time history experienced at a known interior location in the material during the cooling process.

Historically, thermocouples installed at an interior location in the sample have been the most common measurement technique to infer the heat flux at the surface of the sample as well as the sample surface temperature using an IHC model. Figure 1 shows a schematic of a typical thermocouple used to measure the temperature history in a sample during a quench operation. Referring to Figure 1, a thermocouple is made up of two wires, and typically an insulating material such as MgO is used to separate the two TC wires from each other. The thermocouple assembly is then covered using a metal sheath. In situations where the temperature changes rapidly during the quench operation, the thermocouples are positioned within the sample so that the thermocouple tip is very close to the quench surface. This ensures that the detailed changes in the heat flux during the quench operation can be captured. It is important that the thermocouple bead, which is located at the temperature measurement point, has intimate contact with the sample so that the thermal resistance between the thermocouple and sample is reduced.

Although there are many situations where the perturbing effect of the thermocouple hole on the heat propagation within the sample is negligible, there are some cases where the effect of the thermocouple hole can be quite significant.
These can arise when the thermal properties inside the TC hole are significantly different from the surrounding test sample and the heat extraction at the surface of the sample is large. Under these circumstances, the thermocouple hole can perturb heat propagation in the sample and result in erroneous measurements of the temperature.

To date, only a few studies have investigated the perturbation of the thermal field around the thermocouple tip and the resulting error in the heat flux calculation due to the presence of the hole behind it.[6,7,8] Although these studies address some of the issues surrounding the discrepancies in the measured thermal history between a location with a TC hole and a location without a TC hole and resulting errors in the predicted heat flux caused by the thermocouple hole, they are restricted to cases where the heat flux is constant or varies in a linear manner at the surface. The studies have also not assessed the effect of important parameters such as sample thermal conductivity, quench intensity at the surface, thermophysical properties of the hole, or orientation of the hole with respect to the quenched surface on the discrepancy in the temperature measurement as well as the predicted heat-transfer conditions at the surface of the sample.

This article attempts to provide a detailed analysis of the discrepancy in the measured temperature around a subsurface thermocouple as compared to a region without a TC hole. In addition, the error in the inferred surface heat using the thermal history measured by the TC as an input to an IHC model will be quantified. The analysis was done for quench conditions characterized by boiling water heat transfer. The analysis includes factors such as the thermophysical properties of the hole, the geometry of the hole in terms of its diameter and distance from the quenched surface, the thermal conductivity of the material being quenched, and the orientation of the hole relative to the quenched surface. Experimental measurements using TCs located perpendicular (90 deg), parallel (0 deg), and at 45 deg to the quench surface for both steel and aluminum plates were also performed to validate the IHC model predictions. Using this information, situations where the TC hole must be treated as an independent body with its own geometry and thermophysical properties during heat-transfer analyses are outlined.

**II. MATHEMATICAL MODEL**

Finite element (FE) thermal conduction model simulations were run to simulate the effect of a hole used to install a thermocouple and the resulting discrepancy in the temperature-time history measured by a TC on a sample experiencing a water quench characterized by boiling water heat transfer. Three orientations of the TC hole with respect to the sample surface were modeled, namely, perpendicular (90 deg), parallel (0 deg), and at an angle (45 deg). To simulate the presence of a TC hole perpendicular to the quench surface, two-dimensional (2-D) axisymmetric thermal conduction and IHC model simulations using a code developed and verified at the University of British Columbia (UBC) were done.[8] These models were developed based on the FE method, and were used to calculate the sample thermal field by knowing the boundary conditions (thermal conduction model) or to estimate the boundary conditions (heat flux or heat-transfer coefficient) by knowing the temperature data at an interior known location in the test sample (IHC model).

For the other two TC orientations, three-dimensional (3-D) FE simulations were done to simulate the presence of the TC hole using the commercial software package FEMLAB (Comsol Inc., Los Angeles, CA). It was necessary to go to a 3-D simulation for these two cases as symmetry around the TC hole cannot be assumed.

*Simulation of a Thermocouple Hole Perpendicular to the Quench Surface*

Referring to Figure 2, heat transfer is predominantly in the \( r \)-direction toward the water or quench surface and only weakly in the \( z \)-direction across the sample due to the presence of the hole used to install the thermocouple. Heat transfer in the circumferential or \( \theta \) direction was ignored since a small area (5 mm) around the thermocouple was chosen as the calculation domain. The analysis includes the TC hole as an independent body with its own thermophysical properties and geometry actively participating in heat exchange with the surrounding material. In view of the preceding assumptions, the flow of heat in the sample can be described according to Eq. [1].

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\frac{1}{r} \frac{\partial}{\partial r} \left( k r \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) = \rho C_p \frac{\partial T}{\partial t} \tag{1}
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