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Probe Design to Characterize Heat Transfer during Quenching Process

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Abstract

Four water quenching conditions were tested using an effectively designed thermal probe focusing on component surface temperatures. This paper describes the quenching conditions, probe design, method and equipment used to measure temperature. The quenching conditions characterized include two levels of directed water flow, i.e. 4.2 m/s and 6.6 m/s, and immersion in a more conventionally agitated water tank and a tank of still water. A 304 stainless steel probe was fabricated to measure surface temperature changes at several locations along the probe surface during the quenching processes. Surface heat transfer coefficients were determined from the measured time – temperature data using an optimization method based on sensitivity analysis. The detailed descriptions of the fitting method will be given in a subsequently planned paper.

Introduction

During water quenching, non-uniform heat transfer occurs for several reasons. First, part geometry interacts with the local flow field of the water to alter the local water velocity around the part. Second, overheating of the water produces transient boiling. Film boiling will occur where relatively low water velocities exist over large surface areas, while nucleate boiling will occur where the local water velocity is high enough to disrupt the vapor blanket associated with film boiling, and the part surface temperature is still hot enough to support boiling. If the local water velocity is higher yet, the part surface will be cooled below a level needed to support boiling and pure convective cooling will occur. These phenomena are well known and documented. [1]

Intensive water quenching is one approach used to disrupt nucleate boiling that has been discussed in the literature quite extensively. [2-3] These discussions have focused on the idea that the boiling stages of water quenching can be avoided, and convective cooling accentuated by having a local water velocity that is high enough to continually supply water to the part surface. In effect, the part surface temperature is thought to drop almost instantly upon activation of the water flow. In cases of less than optimum velocity, nucleate boiling may take place, meaning that the part surface drops quickly to the water boiling temperature and remains at the boiling temperature for a period of time before dropping to the ambient water temperature. However, there has been no documentation of actual temperatures during the intensive quenching process. The impetus for this study was to measure temperature histories during intense water quenching and to determine local heat transfer coefficients. To do this a special probe was developed, and optimization-based software was used to determine the heat transfer behavior during intensive quenching processes.   For comparison, temperature histories for quenching in still and agitated water were also measured.

Quench Probe Design and Construction

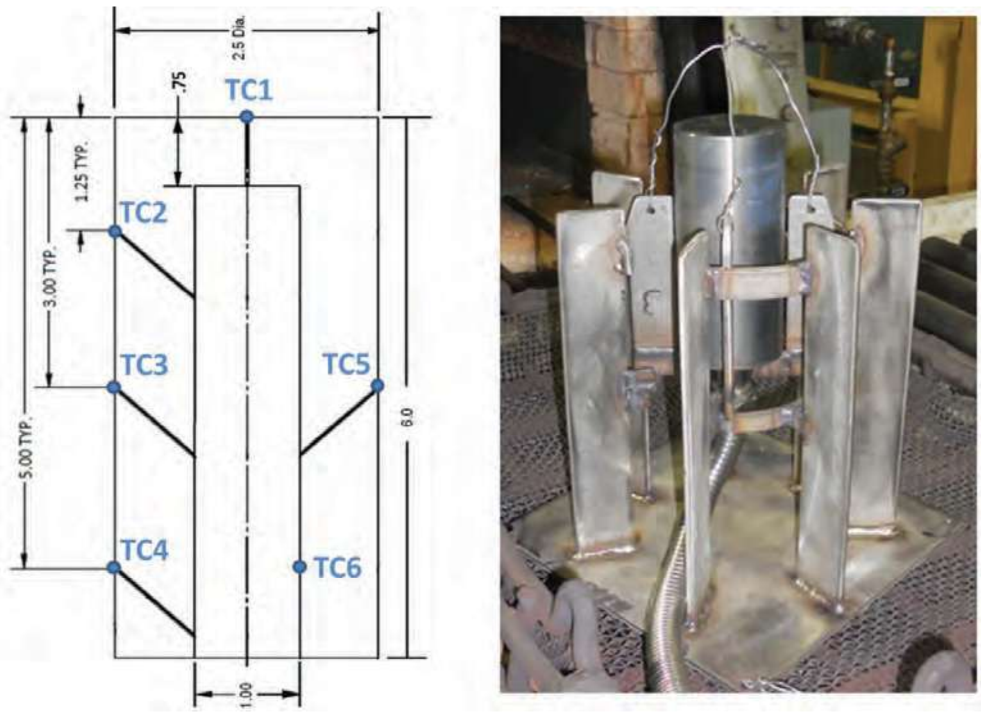
The goal of designing and building a probe to determine the heat transfer during intensive quenching was ambitious due to both the necessary fast response time of the probe and the physical configuration of the production intensive quenching equipment. Commercially available quench probes were not suited to this task because they either could not be adapted to operate within the equipment confines, or were marginal in terms of response time. Therefore, a specialized probe was designed and built for this investigation. The objective was to measure surface or near-surface temperatures at several locations on a cylindrical body during single chamber intensive quenching process. The probe itself would be the "part" being intensively quenched. Several thermocouples would be mounted in the probe so that local temperatures would be measured simultaneously. The temperatures would be measured at a rate of at least 100 Hz in order to capture the rapid temperature change in the part surface during quenching. A PC-based data acquisition board and software to control the temperature measurement rate and to store the data completed the probe system equipment.

A 304 stainless steel bar with a diameter of 63.5 mm (2.50 inches) and length of 152.4 mm (6inches) was procured. Figure 1(a) is a drawing of the probe body, showing a blind hole of 1.0 inch in diameter machined down the centerline. The drawing also shows that fine holes of 0.864 mm (0.034 inches) in diameter were machined at approximately 45° to the bar axis by electrical discharge machining (EDM).

Chromel-alumel (type K) thermocouples sheathed in Inconel with an outer diameter of 0.813 mm (0.032 inches) and with grounded tips were used. The sheathed section was 7.6 m (25 feet) long, with a Teflon jacketed extension wire to make a total length of about 10.7 m (35 feet). The thermocouple accuracies were certified by the commercial supplier. The thermocouples were inserted into the EDM'ed holes, with the tips being flush with the outer surface and the leads extending from the probes blind hole. The thermocouples were brazed in a vacuum furnace to secure them within the probe body. In addition to the five thermocouples brazed into the holes, one thermocouple was brazed to the bore, with the tip roughly 25 mm (1 inch) into the probe bore from the open end.

An austenitic stainless steel cross and a female threaded fitting were welded to the open end of the probe to accommodate the bundled thermocouple leads. The bundled leads were inserted into a 25 mm (1 inch diameter) flexible cable, 7.6m (25 feet) in length, made of austenitic stainless steel.   The purpose of the stainless steel cable was to protect and support the fine thermocouple wires during heating, handling and the intensive quenching process.

IQ Technologies designed a stand to hold the probe during furnace heating and to provide a station from which to grab the probe for transfer to the intensive quenching unit.   The cold probe mounted in the stand is shown in Figure 1(b). This is the same orientation that the probe must maintain during intensive quenching where the water flow would be in the vertically downward direction. Also evident in this figure are cross wires that were used to carry the hot probe from the furnace to the intensive quenching station.



(a) (b)

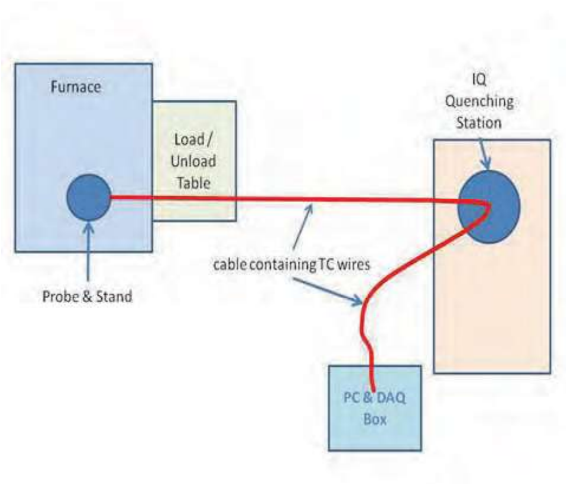
Figure 1   (a) Drawing of 304 SS Quench Probe Body Showing Thermocouple Locations, and (b) Probe Loaded onto Furnace Stand Prior to Loading into the Heated Furnace.

Probe in Use

During intensive quenching the system is sealed in order to contain the high velocity water during quenching. Therefore, the free end of the cable containing the thermocouple leads had to be inserted down through the quenching station and out through a port in the side wall of the drain tube under the quenching station. The free ends of the thermocouple wires were then connected to the data acquisition box and remained connected during the tests. The cable was sufficiently long so that it could be pulled through the station during transport of the probe to and from the furnace to the quenching station. This is shown schematically in Figure 2(a). Figure 2(b) shows the actual cable entering and exiting the intensive quenching station.

The cold probe was loaded into the stand as Figure 1(b) shows, and a wire tray holding the stand was pushed into the hot furnace. The furnace temperature was 870˚C (1600˚ F). During heating, the furnace door was left partially open, with about a 38 mm (1.5 inch) gap at the bottom to accommodate the cable containing the thermocouples. The probe data acquisition system was turned on, with a collection rate of 0.17Hz to collect the heat-up data. The probe was soaked for 20 minutes after the thermocouples showed that the set-point had been reached.

Prior to removal of the hot probe from the furnace, the data acquisition system was activated with a collection rate in excess of 100Hz for each thermocouple channel. The furnace door was then opened and the wire basket was pulled from the furnace. The hot probe in the hot furnace stand is shown in Figure 3. Also evident in Figure 3 is the hot cable that protects the thermocouple wires. Using a pole with the hook, the probe was lifted to the stand and carried several meters to the intensive quenching station. At the same time, the cable was pulled through the station opening so that the probe could be inserted into the station receptacle and the station sealed quickly for intensive quenching to begin.



(a)

(b)

Figure 2 (a) Schematic of Intensive Quenching Test Setup, and (b) Cable Threaded Through the Intensive.

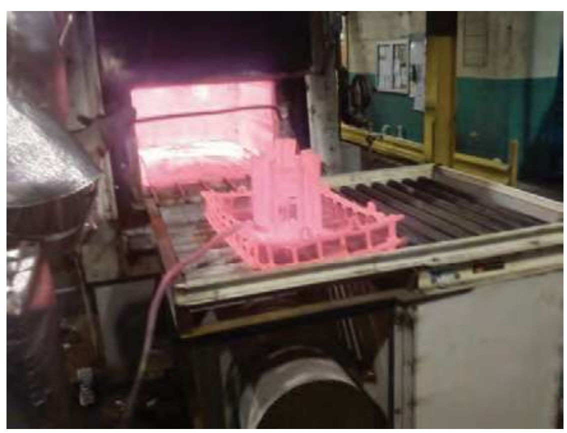


Figure 3 Hot Probe in Hot Stand After Removal from Furnace.

Results & Discussion

Table 1 shows the quenching tests conducted with the probe. For the intensive quenching tests, the water flow rate, aim velocity and quench time are specified. Time-Temperature data are presented in a series of graphs for these tests. During the tests, not all thermocouples functioned, as will be evident by the absence of some data for specific thermocouples.

Table 1 Schedule of Quenching Tests.

Test Number	Type of Test	Flow Rate	Velocity	Quench Time
1	Intensive Quench	1000 gpm	6.6 m/s	200 seconds
2	Intensive Quench	600 gpm	4.2 m/s	40 seconds
3	Water Quench	Agitated	Estimated 0.75 m/s	120 seconds
4	Water Quench	Still	0	120 seconds

Test #1 – Intensive Quench for 200 Seconds

Figure 4 shows the heating data for the cold probe and cold stand loaded into a furnace heated at 870˚ C. Data were collected for 15 minutes, stopped for 4 minutes, and then resumed for 15 minutes during the heating. The probe was then soaked for 20 minutes upon reaching temperature.

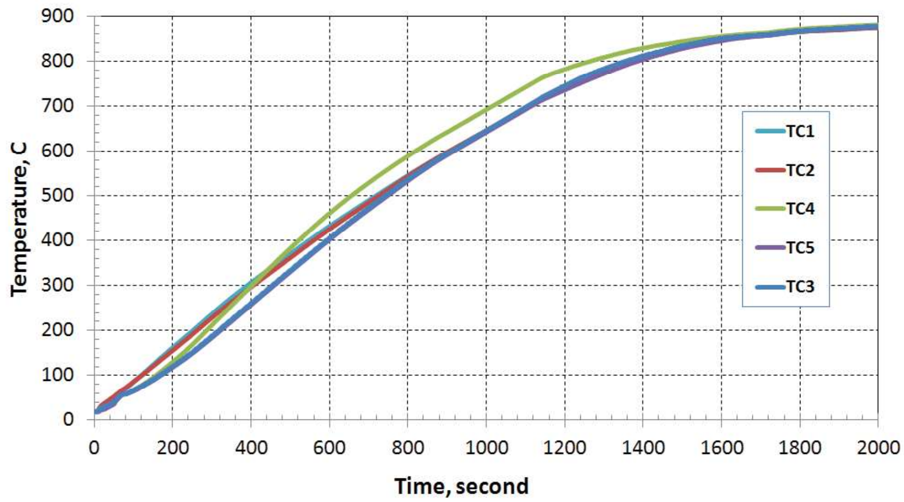
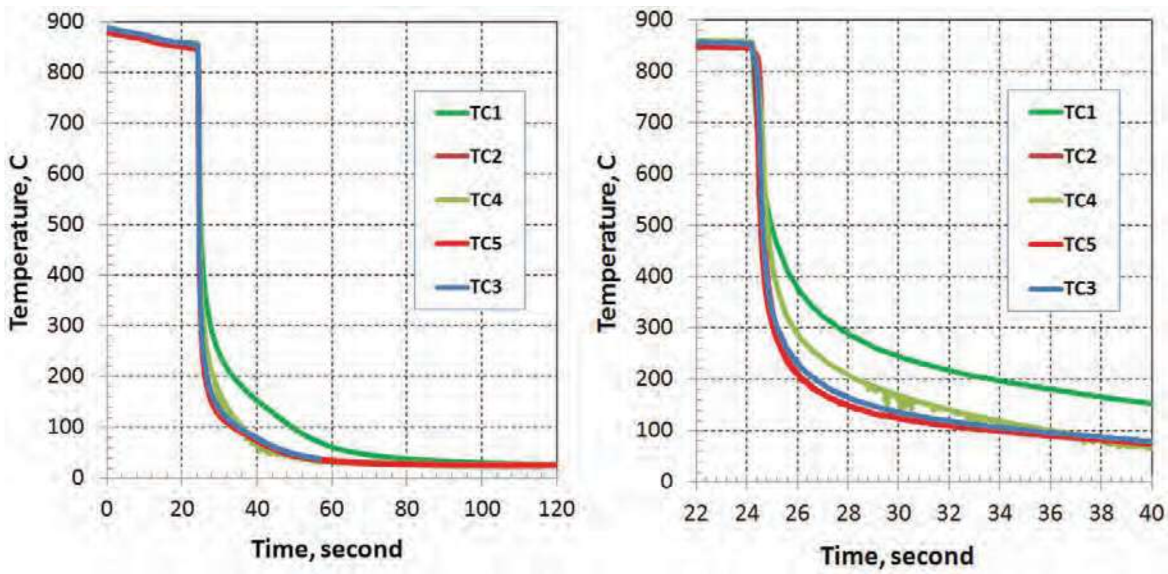


Figure 4 Heating Data for Test #1.

Before removing the probe from the furnace, the data collection system was restarted at 100Hz. The total time for transfer to the quench station was about 20 seconds before the station was closed and intensive water flow was initiated. Figure 5 shows the temperature vs. time data throughout the transfer and quenching portion of the process. Figure 5b is a magnified view of the early seconds of the intensive quenching process. TC1, centered on the top of the probe, initially cooled rapidly as water flow develops, but then cooled much slower than the TC's on the side of the probe. Under full vertical flow, a nearly stagnant zone existed around TC1. TC4, located 1 inch from the bottom end of the probe, experienced some fluctuations as shown, but still produced useful data. TC's 3 and 5, located at mid-height on opposite sides of the probe, cooled in a similar manner, indicating relative uniformity of heat transfer around the circumference of the probe. In general, TC's 2, 3 and 5 cooled faster than TC4.

During the 200 second hold, there was considerable vibration of the probe in the IQ station. This was observable as a loud rumbling noise. Removal of the probe from the station showed that the threaded coupling holding the cable to the probe body had become loose and the thermocouple wires were holding the cable in place. The stress on the shielded TC wires was high and caused some damage that showed up in subsequent tests.



(a) (b)

Figure 5 (a) Quenching Data for Test #1, (b) Magnified View of Initial Quenching Data for Test #1 .

Test #2 – Intensive Quench for 40 Seconds

The heat up timing was similar to that in Test #1 since the probe and stand were again cold at the start. Figure 6 shows the temperature data for TC2, TC3 and TC5 for this test during quenching; TC1 and TC4 did not function in a totally suitable manner during this test, and their data were disallowed. The temperature drop during the transfer period was about 20 to 30 ˚C (36 to 54 ˚F). During intensive quenching the temperature drop was several hundred degrees per second for about 3 seconds.

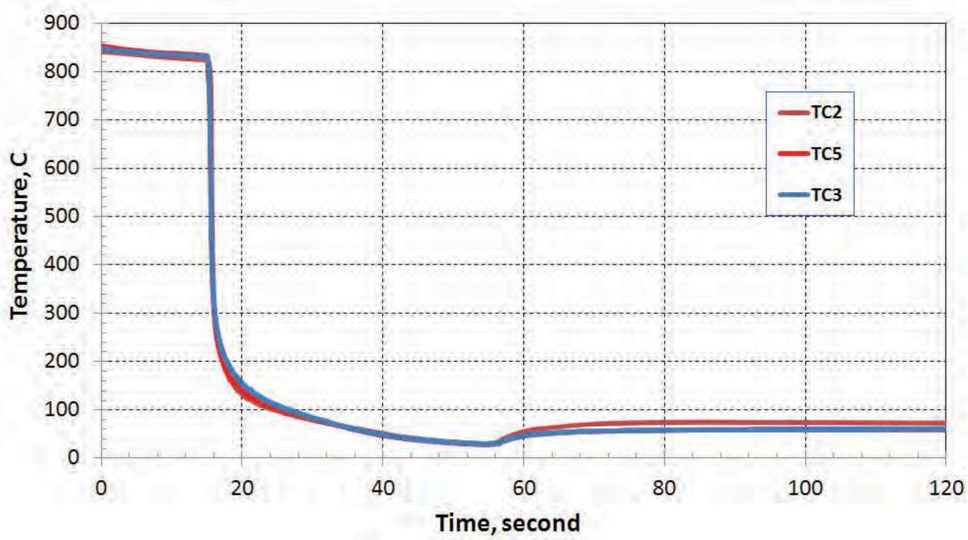


Figure 6 Quenching and Air Cooling Data for Test #2.

After 40 seconds the probe was removed from the quenching station and returned to the stand to finish cooling. The temperature rebound on the surface of the probe is evident for this final air cooling period.

Test #3 – Quench in Agitated Water

In this test, the 3000 gallon holding tank that was used to supply the water for intensive quenching was used as the quench tank. With the intensive quench pumping system running and valves directing water back into the water tank, the agitation is similar to a conventional tank. This is judged purely by appearance of visible water motion, as no assessment of water flow within the tank was undertaken.

After reaching set-point and soaking for 20 minutes, the probe was dunked into the agitated water. The probe orientation was somewhat off-vertical, and the intent was to be perfectly vertical. The temperature vs. time curves for quenching in the agitated water tank are shown in Figure 7. Film boiling is evident during a 2 to 3 second period upon immersion, followed by rapid cooling associated with nucleate boiling. At surface temperatures below 200 C but above 140 C, the cooling rate is low and this period lasts for about 10 to 12 seconds. This period is a combination of boiling and convection, but it is obviously not the violent boing associated with nucleate boiling. At about the 30 second time, pure convective cooling becomes dominant.

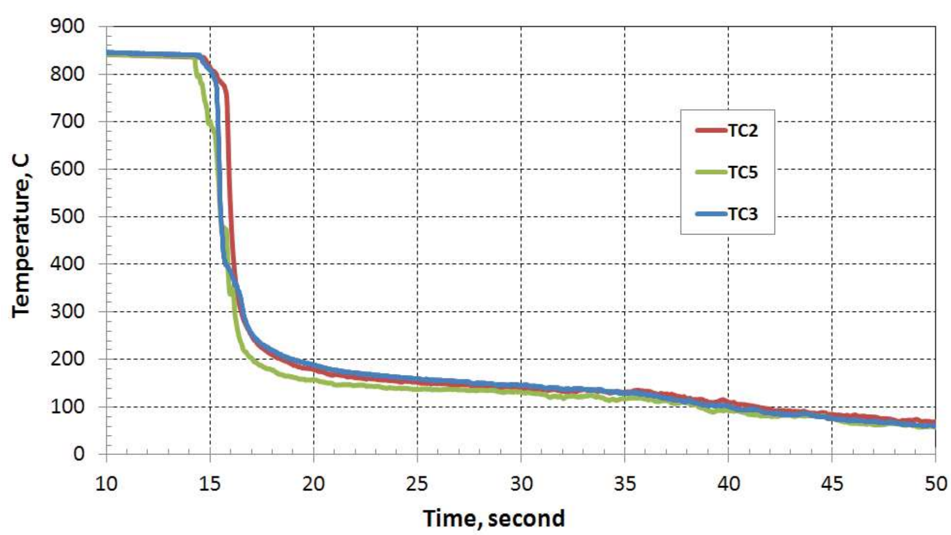
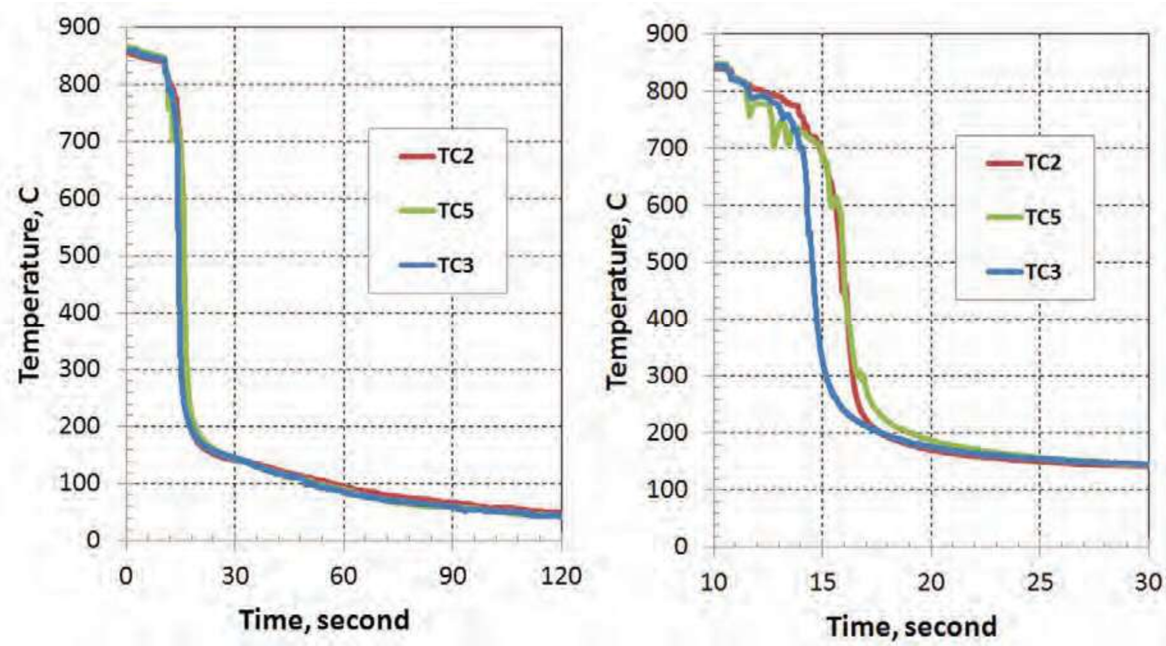


Figure 7 Data for Agitated Water Quench - Test #3.

Test #4 – Quenching in Still Water

The last test involved quenching the probe in the water tank with the pumping system deactivated such that the water was un-agitated or still. Figures 8a and 8b show the thermocouple responses during the still water quench. What is apparent is that considerable boiling occurred during the quench. The large bounces in the curves are due to large bubble formations that locally slow quenching, burst to allow the surface to rewet, and then new bubbles reform. This type of film boiling took place over about a 4 to 5 second time period, and then gave way to nucleate boiling that was rapid and continuous for about the same time period. As the rate of temperature decline slows, convection became the dominant heat transfer mode. This is classic cooling during quenching in a liquid that boils.



(a) (b)

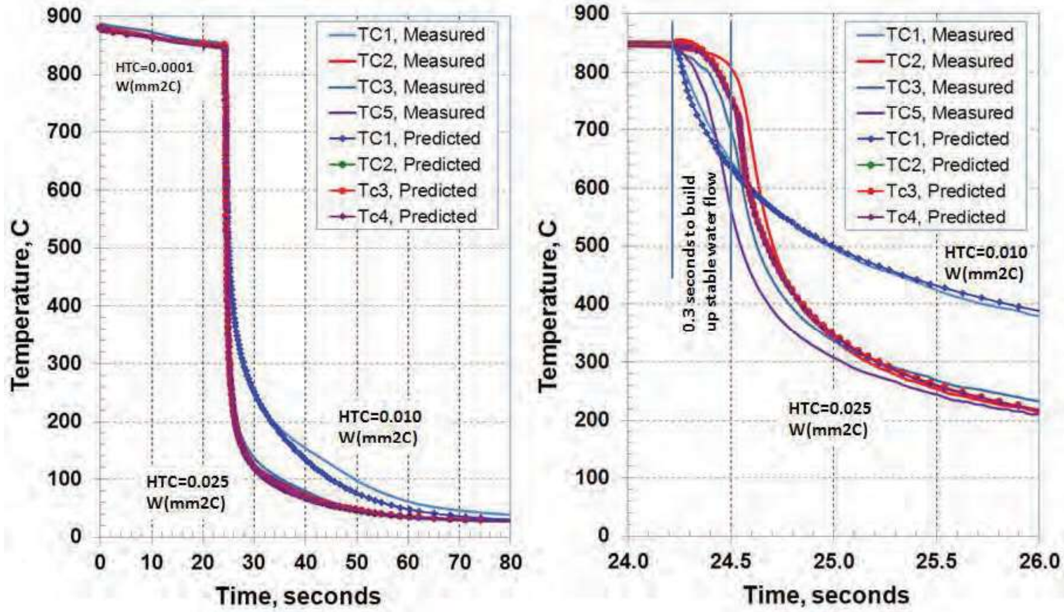
Figure 8 (a) Data for Quenching in Still Water - Test #4, and
(b) Magnified View of Initial Data for Quenching in Still Water - Test #4.

Heat Transfer Coefficients for Intensive Quenching

The cooling data from the probe are needed to determine the surface heat transfer during quenching. Using DCT's software DANTE-HFIT, the thermocouple data was used to determine the heat transfer coefficient values. To accomplish this, a finite element model of the quench probe was developed. The outer surface was broken into zones that were assigned to the various thermocouples. The sensitivity method was then applied that minimized the error between measured and calculated temperatures vs. time at each thermocouple location. The finite element model was run iteratively with changes made in the heat transfer boundary conditions until the cumulative error between calculated and measured values fell below the specified value. Transfer from the furnace to the quench was included in the analysis, as was the time needed to transition from no flow to full water flow for intensive quenching. The following figures show the results for applying this method to the two intensive quenching trials.

Measured versus calculated data for the indicated quenching trials are shown in Figures 9 and 10. Figures 9a and 9b relate to Test #1, and Figures 10a and 10b relate to Test #2. The general heat transfer coefficient along the probe body determined for trial #1 was 25 kW/(m^2*K) and for trial #2 with the slightly lower water velocity was 22 kW/(m^2*K). In both cases the heat transfer at the top of the probe (TC1) was 10 kW/(m^2*K) due to the presence of a nearly stagnant flow zone.

From Figures 9 and 10 it is clear that it is important to consider both the transfer time to the quench and the time to develop full water flow. These process nuances are important in defining the temperature profile that develops within the part being quenched during the early stages of the process as these directly affect the part total thermal history.



(a) (b)

Figure 9 (a) Predicted and Measured Temperature vs. Time Results for Test #, and (b) Magnified View of the Temperature vs. Time Predictions and Measurements for Test #1. Time for Achieving Full Water Flow is Identified.

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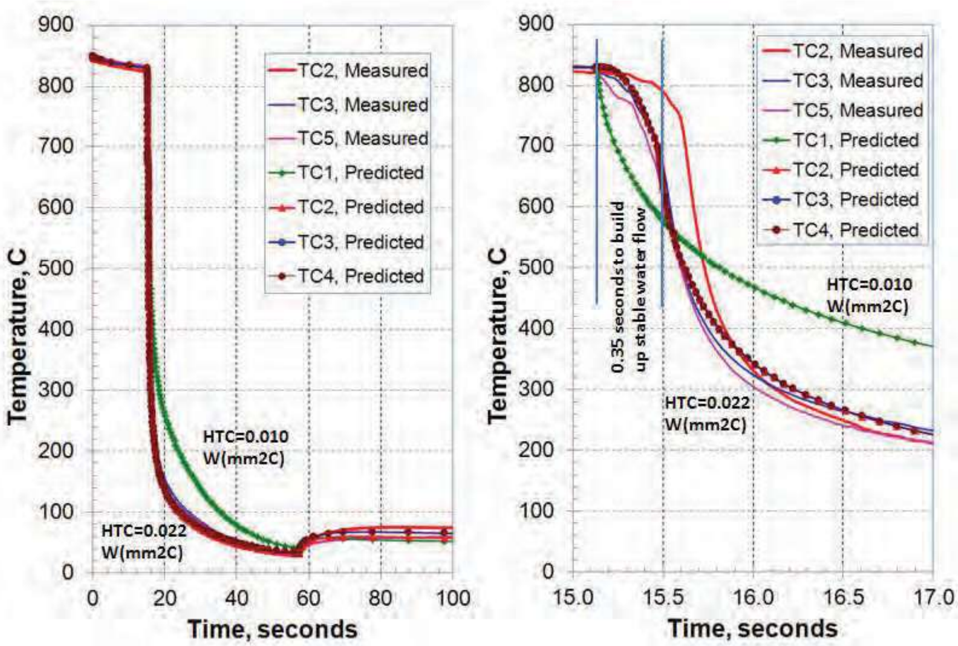

(a) (b)

Figure 10 (a) Predicted and Measured Temperature vs. Time Results for Test #2, (b) Magnified View of Predicted and Measured Temperature vs. Time Results for Test #2 Showing Transition Period to Full Water Flow.

Conclusions

This study showed that heat transfer coefficients on the order of 22 to 25 kW/(m^2*K) were easily achieved during intensive quenching of a relatively large cylinder. A probe system was designed and built that had the capability of measuring and recording the temperature data needed to calculate the heat transfer coefficients for such rapid temperature changes.

Also demonstrated was the capability of interrogating the test data to discover specific details about a process, such as transfer times and temperature drops, the water flow initiation period for a particular quenching set-up, and examining the effect of quench interruption on part temperature.

Of primary significance is a general observation that further work in developing experimental and analytical methods similar to those employed in this study are needed to develop heat transfer data for use in computational heat treatment design. The investigation showed that it is possible to successfully develop a quench probe for use in a complex quenching production unit.

Finally, the use of agitated water and still water during quenching and the presence of film and nucleate boiling on surface heat transfer coefficients were also investigated. Heat transfer coefficients relating to the still water condition will be further investigated and reported in a subsequent paper.

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