An Experimental Study of Heat Transfer During Forced Air Convection

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Cast aluminum alloys are usually subject to solution treatment, quenching, and aging hardening for improved mechanical properties. Cooling rate during quenching plays an important role in residual stress, distortion, and mechanical property distributions in the resultant cast aluminum components. As the cooling rates of work pieces heavily depend on the interfacial heat transfer coefficient (HTC) between work pieces and quenchants, it is important to understand how HTC varies with different quenching conditions so that optimal quenching process can be achieved. In this study, a quenching system and an experimental procedure of obtaining HTC are presented. A series of experiments have been conducted to study the variations of HTC with respect to air temperature, air humidity, air velocity, and part orientation.

1. Introduction

Aluminum alloy castings are widely used in automotive industry to reduce weight and improve fuel efficiency. To improve mechanical properties, cast aluminum components are usually subjected to heat treatment including a solution treatment at a relatively high temperature, quenching in a cold medium such as water or forced air, and then aging hardening at an intermediate temperature.

Quenching after solutionization is to freeze strengthening elements in aluminum matrix to form a supersaturated solid solution for subsequent precipitation hardening. Rapid quenching usually favors hardness and tensile strengths, but it can produce a significant amount of residual stresses and distortion in cast aluminum components. Forced air quenching has been thus increasingly used in heat treatment of cast aluminum components for a combination of high mechanical properties and low residual stress. Compared to liquid quenching systems, the forced air quenching has several advantages: (A) being more environmentally friendly; (B) involving milder quenching for reduced residual stress and distortion; (C) affording more controllable cooling rate and then more uniform temperature distribution in the quenched object by adjusting the heat transfer coefficient (HTC) between the surface of the component and the forced air flow (Ref 1-4).

Experimental and numerical simulation results have shown that the convection HTC between the component and the

quenching gaseous media plays an important role in the resultant distortion, residual stress, and hardness distribution of the quenched object (Ref 1, 3, 5). It is thus important to understand how HTC varies with different quenching conditions so that an optimal quenching process can be achieved.

Various empirical equations have been proposed and reported in the literature to calculate HTC for different fluids using dimensionless Reynolds number, Prandtl number, and Nusselt number (Ref 6-9). For a particular case with a specific part geometry and quenching condition, the HTC can be determined to a certain degree of accuracy by carefully selecting the related empirical model. In practice, however, the HTC is not readily calculated since it is a function of various factors such as air temperature, air velocity, surface quality, and part orientation. This article is aimed to attain a better understanding of convection heat transfer of cast aluminum components in the forced air quenching and the influence of various air quenching process variables on the HTCs. Center for Heat Treating Excellence (CHTE) at WPI has built a quenching system for quenching experiments with small cylindrical probes to study water, oil, and gas quenching (Ref 10-13). In this study, the quenching system has been modified to study air quenching. The HTCs of the cast aluminum probe at different quenching conditions were determined experimentally and compared with Churchill and Bernstein's model's predictions. This study also presents an application of the experimentally determined HTC in an FEA simulation.

2. Experimental Plan

To determine the effects of air velocity, air temperature, relative humidity, and part orientation on air cooling of cast aluminum alloy 319, the following experiments, as shown in Table 1, were conducted.

Three air velocities in the range from 4.8 to 18 m/s were chosen representing current industrial production variations. The air temperature and its relative humidity were selected with respect to weather and season restrictions. Three different part

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quenching orientations were selected including vertical, horizontal, and 45° (relative to the forced air flow direction).

3. Experimental Procedure

3.1 Air Quenching System

Figure 1 shows the air quenching system at CHTE. As shown in Fig. 1, a variac is used together with an anemometer (accuracy of ±0.1 m/s) to adjust the input voltage of the blower and to set the air velocity in the working area, so that the air velocity can be adjusted from 3 to 20 m/s. The 8-in. (203-mm) diameter blower outlet is relatively very big compared to the small probe, and it is able to find such a working zone where the air velocity is uniform. A heater and a humidifier (not shown in the figure) were used to adjust the air temperature and air relative humidity in the quenching room. A device called weather station was used to measure air temperature and relative humidity. A pneumatic lifting system was employed to lift the probe from furnace to quenching area at a constant speed. A K-type thermocouple was placed at the center of the probe to record the temperature change of the probe during air quenching. The probe is screwed to a ceramic coupling which

is used to prevent heat transfer between the probe and the fixing and lifting components. The ceramic coupling is then screwed to a fixing coupling, which is used to fix the thermocouple with another screw so that the tip of thermocouple will touch the probe tightly. The fixing coupling is then connected to the pneumatic lifting system. The ceramic coupling, fixing coupling, and the lifting rod are all hollow so that the K-type thermocouple can go through them. Figure 2 shows the detailed dimensions of the cylindrical probe. Before experiments, the thermocouple and data acquisition system were calibrated at ice water (0 °C), boiling water (100 °C), and room temperature with other temperature measurement equipment (calibrated by Omega Company).

In the air quenching experiment, the instrumented cylindrical probe together with a reference thermocouple were first lowered into the furnace and heated to 495 °C. After reaching 495 °C, the probe was held for 10 min for a uniform temperature profile before being lifted by the pneumatic lifting system to the quenching area to be cooled down to room temperature. During air quenching, the cooling curve of the probe was recorded via a data acquisition system using a sampling rate of 40 temperature data per second. In addition, system repeatability was evaluated in the experiments, and repeatable data were obtained.

To study the influence of probe orientation on heat transfer of cast aluminum alloy during air quenching, the quenching system shown in Fig. 1 was modified by replacing the fixed sample holder with a rotatable one. After being lifted out of the furnace, the probe was rotated to a specific position for air quenching. Figure 3 schematically shows three different quenching orientations tested in this study.

3.2 Method to Determine HTC

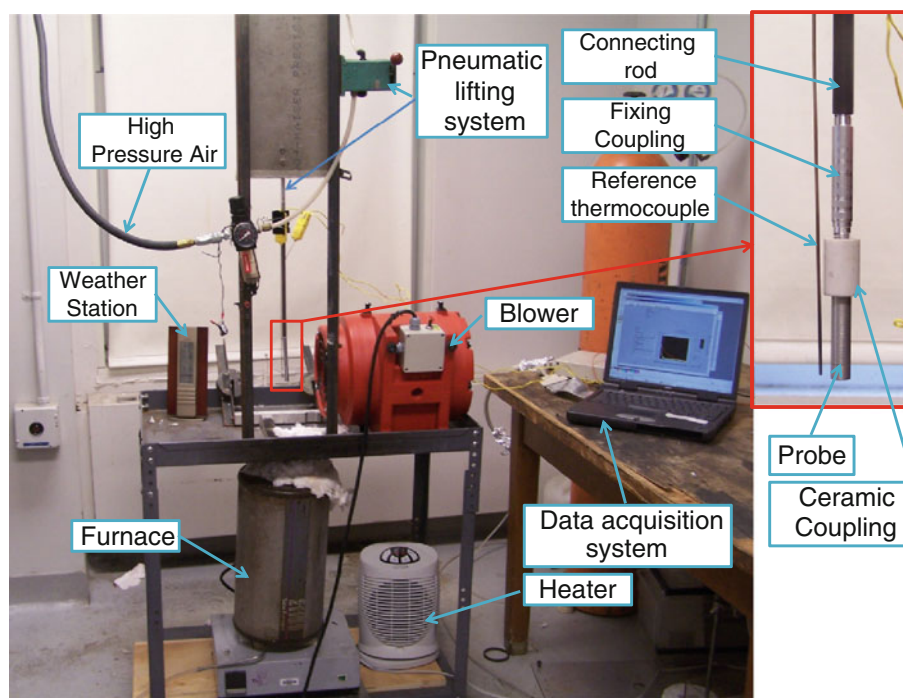The method employed in this study to determine the HTC is simply based on the energy (heat) conservation principle,

Table 1   Experimental test matrix

Probe material	Air temperature, °C	Air relative humidity	Air velocity, m/s	Probe orientation (relative to air flow direction)
Aluminum alloy 319	15	30%	4.8	Vertical
	25	50%	10.5	Horizontal
			18	45°

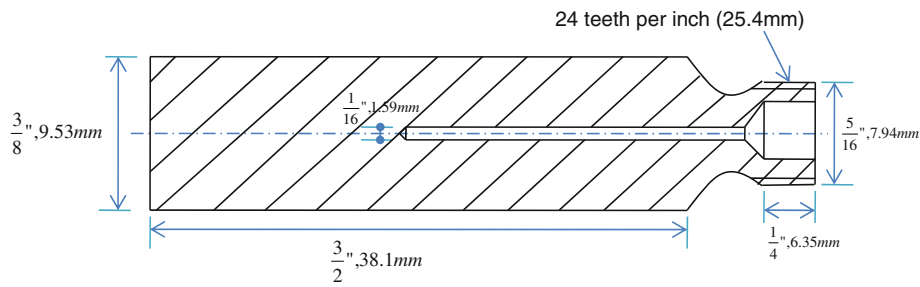**Fig. 1** Experimental system for forced air quenching

Fig. 2 A schematic show of the cast aluminum alloy probe
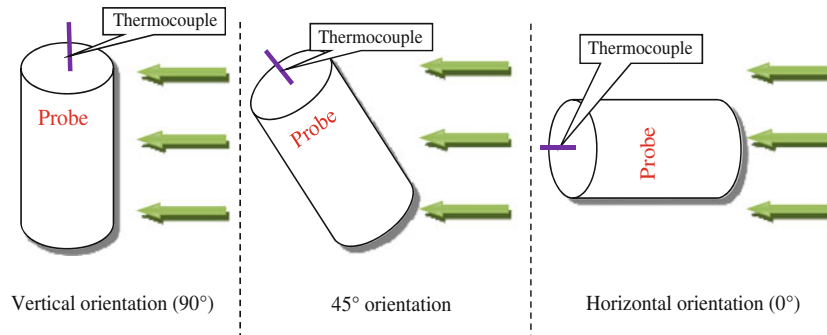

Fig. 3 A schematic show of three quenching orientations

assuming that all the heat lost from the probe during air quenching is transferred to the air flow via convection. Because of the small probe size, and in particular the high thermal conductivity of aluminum alloy, the Biot number calculated by Eq 1 is small (<0.1 for all possible characteristic lengths of the small probe), and thus the temperature field in the probe can be considered uniform during air quenching (Ref 7). The average HTC of the probe can then be determined simply from the temperature-time curve at the center of the probe using Eq 2.

$$\text{Biot} = \frac{h_c L}{K_s} \qquad \text{(Eq 1)}$$

$$h_c = -\frac{m \cdot C_p(T)}{A(T - T_{air})} \cdot \frac{dT}{dt} \qquad \text{(Eq 2)}$$

where h_c is the HTC averaged over the surface area (W/m^2 K), L the characteristic length (m), K_s the solid thermal conductivity (W/m K), M the probe mass (kg), A the probe surface area (m^2), T the temperature of the probe (°C), T_{air} the temperature of the air (°C), and C_p is the specific heat of the probe material (J/kg °C).

In the calculation of cooling rate, dT/dt, background noise in the measured probe cooling curve can introduce a significant error. Any oscillation in the cooling curve will be magnified during differentiating. To eliminate any possible background noise in the cooling curves, a curve-fitting scheme was used in this study. A fourth-order polynomial function provided by Matlab (Ref 14) was employed to smooth the cooling curves. Figure 4 shows an example of the smoothed cooling curve compared with original data (vertical orientation 18 m/s, 15 °C, and 46-50%). With the smoothed cooling curve, a reliable cooling rate and accurate HTC data can be calculated using Eq 2. The specific heat of aluminum alloy 319, which
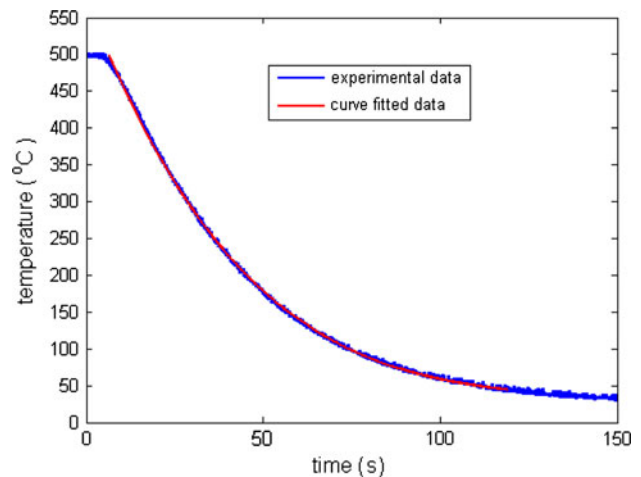

Fig. 4 An example of the smoothed cooling curve compared with the original data obtained at vertical orientation: 18 m/s, 15 °C, and 46-50%

influences the HTC calculation significantly, was also treated as a function of probe temperature in the MATLAB routine. The corresponding cooling rate (absolute value) for the sample cooling curve is plotted in Fig. 5.

Figure 6 shows the corresponding HTC (calculated using Eq 2) versus probe surface temperature. It is seen that the HTC varies slightly (<6%) with respect to probe temperature. To evaluate the influence of various quenching variables on the heat transfer of cast aluminum alloy during air quenching, the HTC data for a given quenching condition are averaged over the probe temperatures in the data analyses of this study.
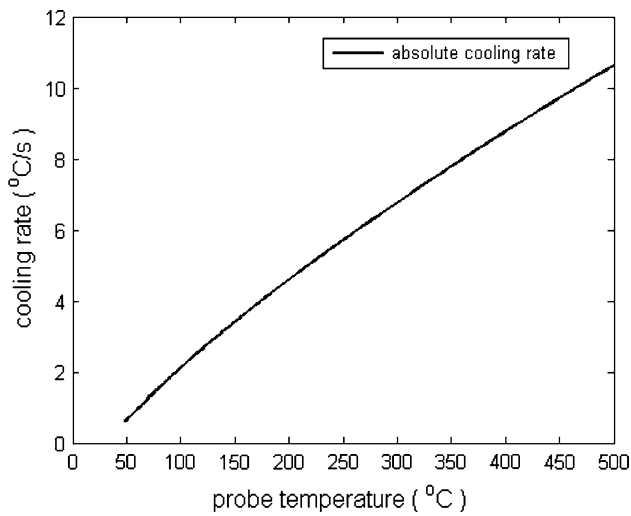
Fig. 5 The cooling rate for the temperature-time data presented in Fig. 4, as a function of probe surface temperature
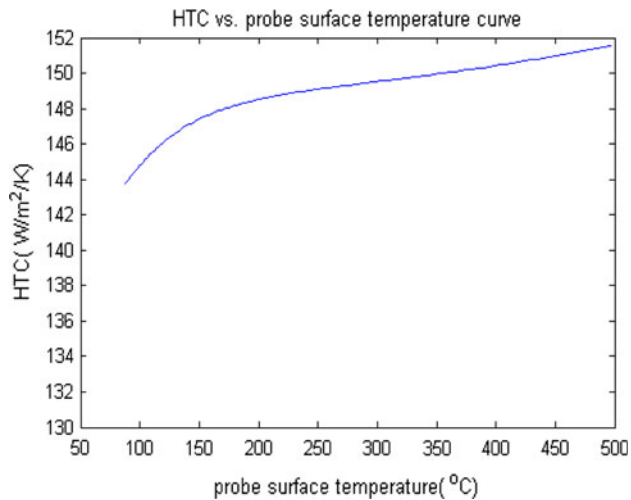

Fig. 6 The calculated HTC for the cast aluminum alloy 319 as a function of probe temperature

4. Experimental Results

Table 2 summarizes the mean HTC values calculated from the experiments under different air quenching conditions.

4.1 Effect of Air Velocity

Figure 7 shows the mean HTC values for the casting tested at different air velocities (vertical orientation, 25 °C, and 31-33%). It is apparent that the air velocity plays a very important role in affecting the HTC. A clear linear relationship indicates that the HTC increases proportionally with air velocity for the air velocity ranging from 4.8 to 18 m/s tested in this study.

4.2 Effect of Probe Quenching Orientation

The HTC data (15 °C and 31-33%) at different orientations are divided by the HTC at vertical orientation, and these ratios are plotted in Fig. 8. It is seen that HTC varies slightly at different quenching orientations. The 45° quenching orientation provides the highest HTC, while horizontal orientation produces the smallest HTC. This is attributed to variations of the local velocity and characteristic length. Compared to 0°
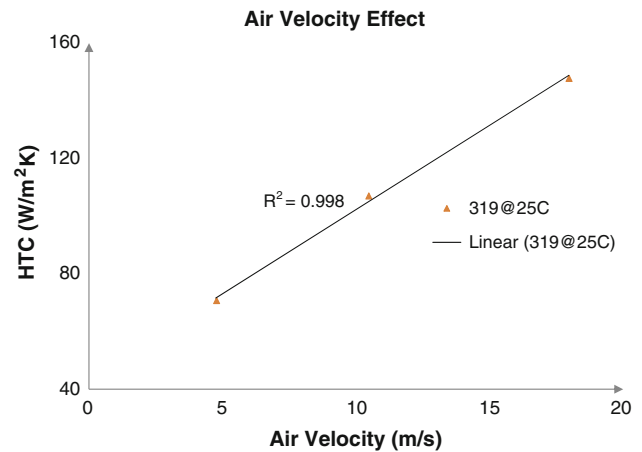

Fig. 7 Effect of air velocity on HTCs of cast aluminum alloy probe quenched under forced air at vertical orientation, 25 °C, and 31-33%

Table 2 Experimentally obtained HTC data

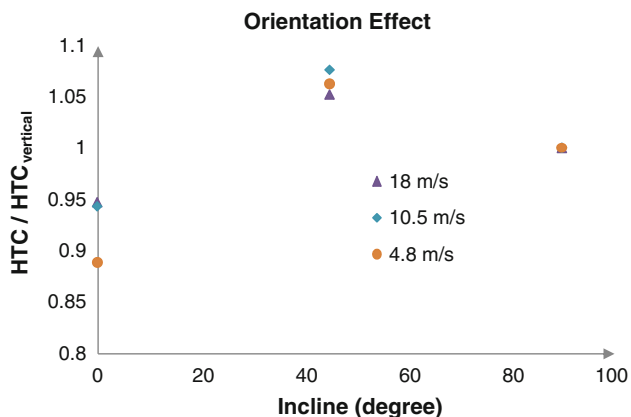| Velocity, m/s	Air temperature, °C	Relative humidity, %	Orientation	HTC experiment 1, W/m² K	HTC experiment 2, W/m² K	Average HTC, W/m² K
18	15	31-33	Vertical	147.97	146.40	147.19
			45°	153.80	155.99	154.89
			Horizontal	139.43	139.32	139.37
		46-50	Vertical	148.71	148.18	148.45
	25	31-33	Vertical	146.48	148.70	147.59
10.5	15	31-33	Vertical	98.66	102.49	100.58
			45°	108.48	107.99	108.24
			Horizontal	93.32	96.32	94.82
		46-50	Vertical	106.04	106.00	106.02
	25	31-33	Vertical	106.29	107.32	106.81
4.8	15	31-33	Vertical	66.90	65.83	66.37
			45°	69.68	71.37	70.52
			Horizontal	58.58	59.32	58.95
		46-50	Vertical	61.90	65.89	63.90
	25	31-33	Vertical	70.50	70.55	70.53

Fig. 8 Effect of quenching orientation on HTCs of cast aluminum alloy probe quenched under forced air at 15 °C and 31-33%

Fig. 9 Effect of air temperature on HTCs of cast aluminum alloy probe quenched at various air velocities and vertical orientation

Fig. 10 Effect of air relative humidity on HTCs of cast aluminum alloy probe quenched at various air velocities

orientation, average local velocity in 45° quenching orientation is slightly higher because of the incline angle. The local velocity in 90° is high, but the characteristic length is the length of the probe that is greater than the diameter leading to a reduction of HTC. That is because HTC decreases with characteristic length (Ref 15).

4.3 Effect of Air Temperature

Air temperature effect is studied by carrying out experiments at air temperatures of 15 and 25 °C, and three different air velocities of 18, 10.5, and 4.8 m/s. For each air velocity, the HTC data at different air temperatures are divided by the HTC at 25 °C, and the ratios are plotted in Fig. 9. For the air temperatures tested in this study, no significant influence of air temperature on HTCs was found, which is similar to the results reported by Still et al. (Ref 16).

4.4 Effect of Air Relative Humidity

The effect of air relative humidity on HTC for cast aluminum alloy probe was studied at 15 °C and three different air velocities of 18, 10.5, and 4.8 m/s and the experimental results are presented in Fig. 10. Similar to air temperature, the influence of air humidity on HTCs is also marginal ($<6\%$), which again is in agreement with Still et al.'s results (Ref 16).

5. Analysis and Discussion

The experimental results were compared to empirical calculation and applied in an FEA simulation.

5.1 Churchill and Bernstein`s Model

The HTCs for gas and liquid flow across simple cylinders can be theoretically estimated using Churchill and Bernstein's model as expressed in Eq 3, which covers the complete range of available data of Reynolds and Prandtl numbers (Ref 9):

$$Nu = 0.3 + \frac{0.62 Re^{1/2} Pr^{1/3}}{\left[1 + \left(\frac{0.4}{Pr}\right)^{2/3}\right]^{1/4}} \cdot \left[1 + \left(\frac{Re}{282000}\right)^{5/8}\right]^{4/5} \quad \text{(Eq 3)}$$
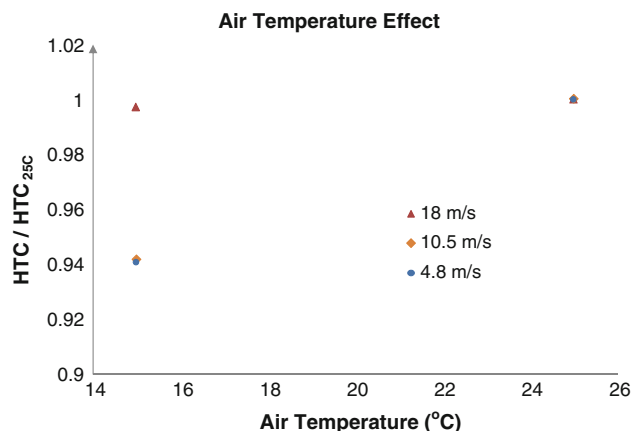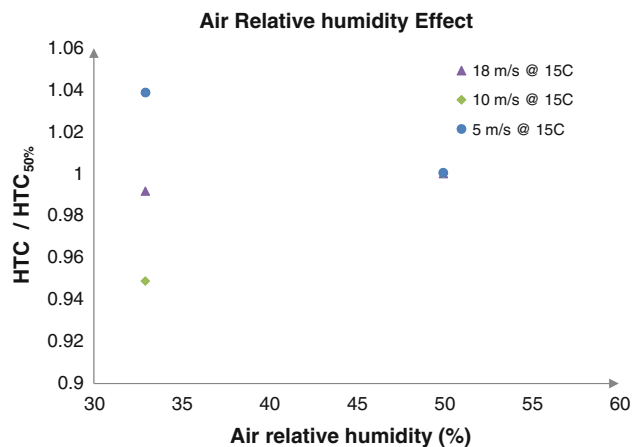
Table 3 Air thermophysical properties at 25 °C

Temperature, °C	Density, kg/m³	Specific heat, W/kg K	Dynamic viscosity, kg/ms	Thermal conductivity, W/m K
25	1.19	1005.38	1.81e-5	0.026

$$Nu = \frac{h_c L}{k_{\text{fluid}}} \quad \text{(Eq 4)}$$

where Re and Pr are Reynolds and Prandtl numbers, respectively, which can be calculated from air thermophysical properties, probe characteristic dimension, and air velocity. HTC can be calculated from the definition of Nusselt number shown in Eq 4 (Ref 6). The air thermophysical properties at 25 °C are listed in Table 3 (Ref 17).

Table 4 compares the calculated HTCs from the Churchill and Bernstein's model (Eq 3) with those of experimental data. The difference between the model predictions and experimental data is relatively small, indicating that the Churchill and Bernstein's model can be used to estimate the HTCs for air flow

Table 4 HTC comparisons for air flow across cylinders (vertical orientation)

Air velocity, m/s	Churchill's equation, W/m² K	Experiment average, W/m² K	Percent difference
18	155.55	147.59	5.39
10.5	115.80	106.81	8.42
4.8	76.46	70.53	8.41

Fig. 11 Finite element simulation

across cast aluminum cylinder. No comparisons were made for other orientation because this empirical equation can only calculate HTC for the vertical orientation.

5.2 FEA Simulation

The experimentally determined HTC values were applied in an FEA simulation to evaluate its usage and accuracy. Figure 11 shows an FEA analytic model for air quenching simulation. In the model, the initial probe temperature is set as 495 °C, and the experimentally obtained HTC is applied to the probe surface for convection heat transfer. Probe material properties such as specific heat, conductivity, and density are defined as functions of probe temperature in the model, as illustrated in Table 5.

The predicted temperature-time curve from the FEA simulation and the corresponding experimental measured curve are compared in Fig. 12. Temperatures from FEA simulation drop slightly slowly in comparison with the experimental measurements, but in general, they are in good agreement. This indicates that the experimentally determined HTC data are of high accuracy and can be applied as thermal boundary conditions in simulation of air quenching.

5.3 The Use of the Ceramic Coupling

In this experimental study, a ceramic coupling was used between the probe and lifting system to minimize the heat conduction between the probe and the lifting system, since the thermal conductivity of ceramic (< 20 W/m K) is much smaller than that of aluminum alloy 319 (139-153 W/m K). A few of experiments without the ceramic coupling were conducted to evaluate how much heat will be conducted between the probe

Table 5 Probe material (aluminum alloy 319) properties

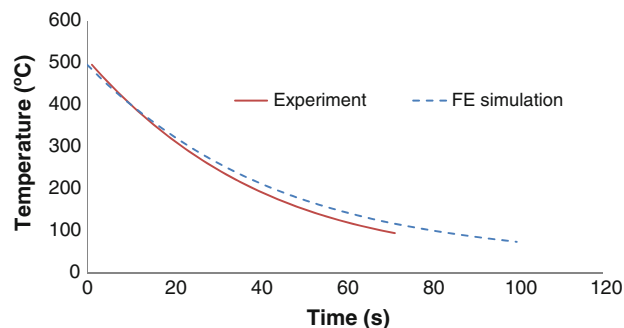| Temperature, °C	Density, kg/m³	Specific heat, W/kg K	Thermal conductivity, W/m K
25	2770	897	139
100	2745	926	141
200	2720	972	150
300	2700	1002	157
400	2670	1080	156
495	2650	1200	153

Fig. 12 A comparison between the simulated cooling curve by FEA using the experimentally determined HTC data and experimental measurement
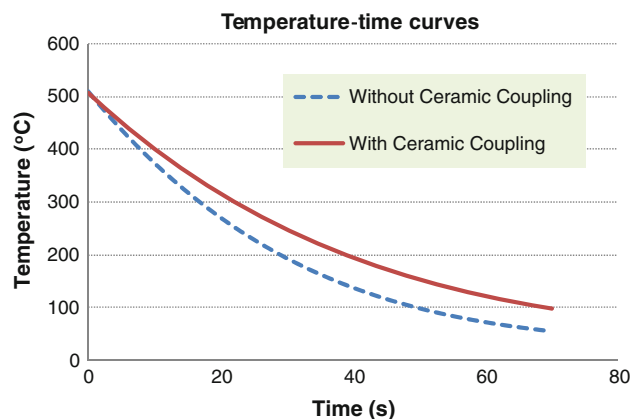

Fig. 13 Measured temperature-time curves with or without ceramic coupling

and the lifting system. Figure 13 shows a comparison of temperature-time curves between experiments with and without ceramic coupling. A significant temperature drop was observed in the experiment without ceramic coupling, which results in that the experimental obtained HTC data are higher than the real HTC data.

Table 6 summarizes the HTC data calculated from the temperature curves measured from the experiments conducted with and without ceramic coupling. It is surprising to note that the error caused by the undesirable heat conduction from the probe to the probe-holding fixture can be as high as 40%.

In this case, the heated fixing coupling was also cooled down in the forced air flow. Because the fixing coupling is hollow, it cools faster than the solid probe. Therefore, the heat was conducted from the probe to the fixing coupling. However, it is not always true that the heat is conducted from the probe to

Table 6 Experimentally obtained HTC data with and without ceramic coupling

Velocity, m/s	HTC with ceramic coupling, W/m² K	HTC without ceramic coupling, W/m² K	Percent error
18.0	147.59	207.82	40.81
10.5	106.81	147.78	38.36
4.8	70.53	93.82	33.02

the fixing components. In some cases, heat might be conducted from the fixing components to the probe. For instance, in some water quenching experiments, only probe is immersed into water and cooled down in water. The fixing components and lifting system, which are also heated in furnace, are cooled slowly by air. Therefore, the temperatures of the fixing components and lifting system are higher than probe, and heat is conducted to probe during quenching. In such a case, experimentally obtained HTCs are lower than real HTC.

6. Conclusions

This article reports an air quenching system and experimental procedures to obtain HTC data under various air quenching conditions. The convection heat transfer of cast aluminum alloy (319) during air quenching has been investigated with a simple cylindrical probe under different quenching conditions including air velocity, air temperature, air relative humidity, and part orientation. It was found that the HTC data increase significantly with increasing air velocity. The probe orientation also affects HTC considerably. The inclined quenching orientation (45°) results in a better heat transfer in comparison with vertical or horizontal orientations. The air humidity and air temperature have little effects on HTC data. The relationship between HTC and air velocity developed in this study can be used in production to optimize the desired air velocity for the required cooling rate.

Acknowledgment

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