Influencing Factors of Heat Transfer Coefficient in Air and Gas Quenching

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Abstract: Cooling rates during quenching play an important role in residual stress, distortion, and mechanical property distributions in the resultant metal components. Because 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 respect to various influencing factors so that the HTC can be well controlled and the optimal quenching process can be achieved. In this paper, the influencing factors such as air/gas velocity, pressure, temperature, gas mixture and part orientation, air/gas temperature, air humidity, surface roughness, oxide and material to the variation of HTC are studied experimentally by using CHTE quenching system and theoretically by using empirical equations.

Keywords: Air Quenching, Gas Quenching, Heat Transfer Coefficient, Influencing Factors, Pressure, Velocity, Orientation

1. Introduction

To improve mechanical properties, cast aluminum and steel components are usually subjected to heat treatment including a solution treatment or austenizing treatment at a relatively high temperature and quenching in a cold medium such as water, forced air/gas. Rapid quenching usually favors hardness and tensile strengths, but it can also produce a significant amount of residual stresses and distortion in the metal components. Forced air/gas quenching has been thus increasingly used in heat treatment of metal components for a combination of high mechanical properties and low residual stress. Compared to liquid quenching systems, the forced air/gas quenching has several advantages: A). air/gas quenching is more environmentally friendly. B). air/gas quenching is milder quenching for reduced residual stress and distortion. C). air/gas quenching has more controllable cooling rates and produces more uniform temperature distributions in the quenched objects by adjusting the HTC between the surface of the component and the forced air flow [1-4].

Numerical simulation and experimental results have shown that the convection HTC between the component and the quenching media plays an important role in residual stress, resultant distortion and hardness distribution of the quenched object [1, 3, 5], therefore, it is important to understand how HTC varies with different quenching factors so that optimal quenching process can be achieved.

This paper aims to have a better understanding of convection heat transfer of metal components in the forced air/gas quenching and the influence of various variables on the HTC. HTC is calculated theoretically by using empirical equations that were proposed and reported in the literature using dimensionless Reynolds number, Prandtl number and Nusselt number [6-9]. For a particular case with a specific part geometry and quenching condition, HTC can be determined to a certain degree of accuracy by carefully selecting a related empirical model. In practice, however, the HTC is not readily calculated since it is a function of various factors such as temperature, velocity, pressure, surface quality, part orientation, etc. Thus, CHTE at WPI has built a quenching system and conducted a lot of quenching experiments with small cylindrical probes to study water, oil and gas quenching [10-14]. Some air quenching experiments were performed to study the influencing factors in air/gas quenching.

2. Determine HTC theoretically

During air/gas quenching, heat is mainly transferred from hot work piece to the surrounding gas flow by convection as expressed in Equation 1.

$$\dot{Q} = h \cdot A \cdot (T_{surface} - T_{gas}) \tag{1}$$

where
$\dot{Q}$ =heat transfer rate, J/s
h =convective heat transfer coefficient, $W/m^{2\,o}C$
A =surface area, m^2
$T_{surface}$ =work piece surface temperature, ^oC
T_{gas} =temperature of the gas, ^oC

Classic empirical equations can be used to calculate HTC in air/gas convection. With the classical heat transfer theory, the dimensionless Reynolds number, Prandtl number and Nusselt number are defined in Equation 2-4, respectively.

$$\mathrm{Re} = \frac{\rho v L}{u} \tag{2}$$

$$\mathrm{Pr} = \frac{C_p u}{K} \tag{3}$$

$$Nu = \frac{hL}{K} \tag{4}$$

where
v = gas velocity, *m/s*
ρ =gas density, kg/m^3
L =characteristic length of the work piece, *m*
C_p =gas specific heat, J/kg^oC
u =gas dynamic (absolute) viscosity, *kg/ms*
K =gas thermal conductivity, W/m^oC

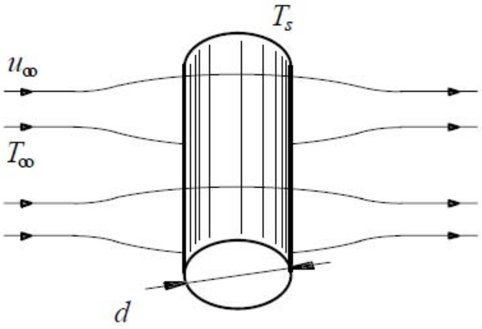

Fig. 1 Flow across a cylinder [15]

The Nusselt number can be calculated from Reynolds number and Prandtl number using empirical equations. For instance, for the case of flow across a cylinder as shown in Figure 1, Equation 5 can be used to calculate the Nusselt number [16]. The corresponding calculation of HTC is expressed as Equation 6. Equation 7 by Churchill and Bernstein is recommended by Holman in his textbook [6] to calculate the Nusselt number [9] since it is applicable for a wider range of fluids and Reynolds numbers. After the Nusselt number is calculated, HTC can be determined from Equation 4.

$$Nu = 0.023 \cdot \mathrm{Re}^{0.8} \cdot \mathrm{Pr}^{1/3} \tag{5}$$

$$h = C_1 \cdot (\rho v)^{0.8} \cdot u^{-0.47} C_p^{0.33} K^{0.67} L^{-0.2} \tag{6}$$

where C_1 is a constant.

$$Nu = 0.3 + \frac{0.62\,\mathrm{Re}^{\frac{1}{2}}\,\mathrm{Pr}^{\frac{1}{3}}}{[1+(\frac{0.4}{\mathrm{Pr}})^{\frac{2}{3}}]^{\frac{1}{4}}} \cdot \left[1+\left(\frac{\mathrm{Re}}{282000}\right)^{\frac{5}{8}}\right]^{\frac{4}{5}} \tag{7}$$

3. Determine HTC experimentally

The method employed in this paper to determine HTC is simply based on the energy (heat) conservation and the assumption that all the heat lost of the probe during quenching is transferred to the fluid flow via convection. Because of the small probe size and the high thermal conductivity of the probe, the Biot number calculated by Equation 8 is small (less than 0.1) and thus the temperature field in the probe can be considered uniform during quenching [7]. The average heat transfer coefficient of the probe can then be determined simply from the cooling curve at the center of the probe using Equation 9.

$$Biot = \frac{hL}{K_s} \tag{8}$$

$$h = -\frac{m \cdot C_{ps}(T)}{A(T - T_{air})} \cdot \frac{dT}{dt} \tag{9}$$

where:

K_s -solid thermal conductivity, W/m^oC
m-probe mass, kg
T-temperature of the probe, ^oC

T_{air} -temperature of the air, ^{o}C

C_{ps} -specific heat of the probe material, $J/kg^{o}C$

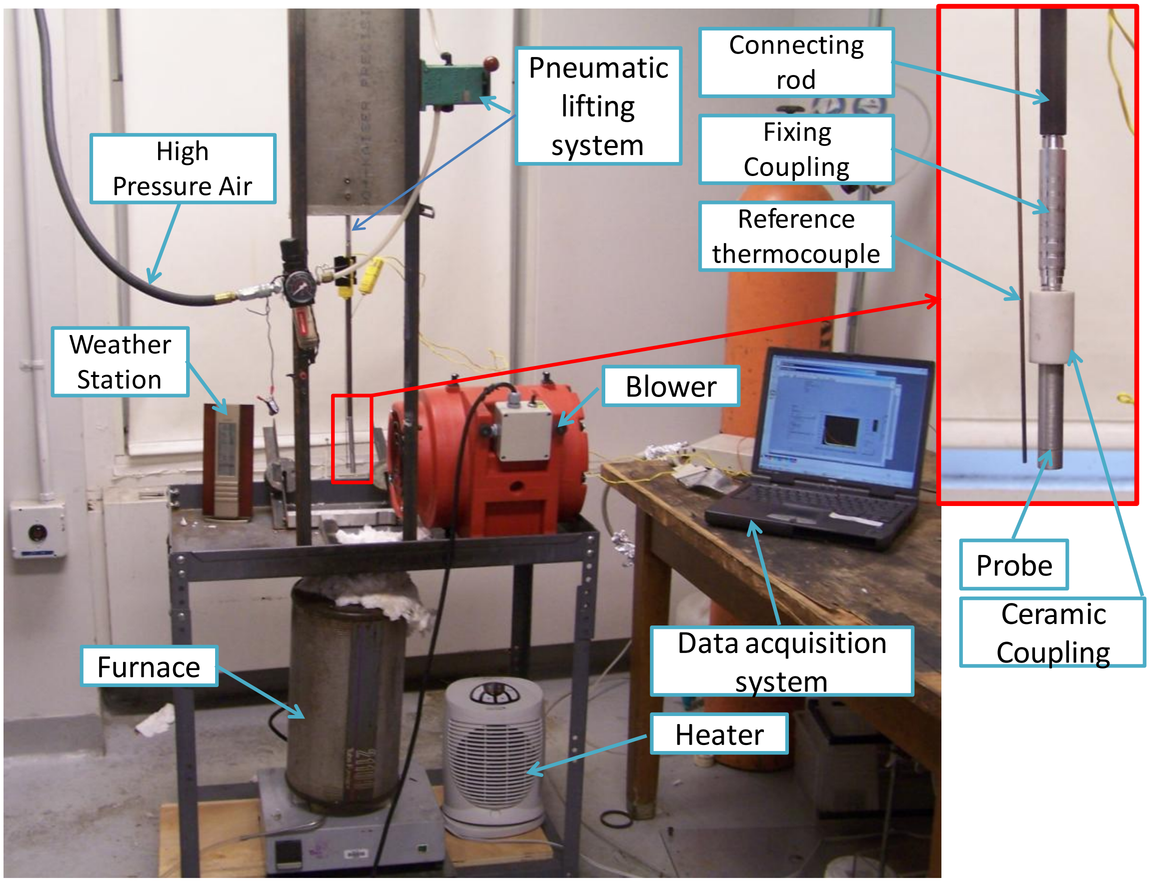

Fig. 2 Experimental system for forced air quenching

Fig. 3 shows an example HTC curve that is quite independent of probe temperature, therefore, in the followed factor study, the average HTC over the whole quenching process is used.

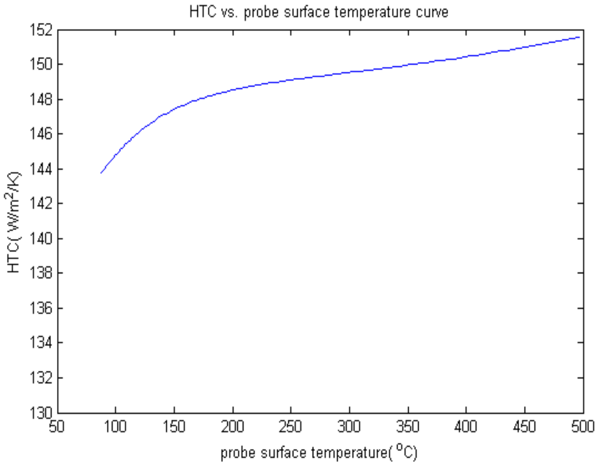

Fig. 3 The calculated HTC for the cast aluminum alloy as a function of probe surface temperature.

4. Factor Analysis of HTC in Air and Gas Quenching

Various influencing factors such as air/gas pressure, velocity, temperature, mixture, part orientation, material, surface roughness and oxide are studied.

4.1. Air/gas velocity effect

Experimentally obtained HTCs for quenching aluminum alloy probe at different air velocities are plotted in Fig. 4. 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 respect to air velocity for the air velocity range from 4.8 m/s to 18 m/s tested in this work.

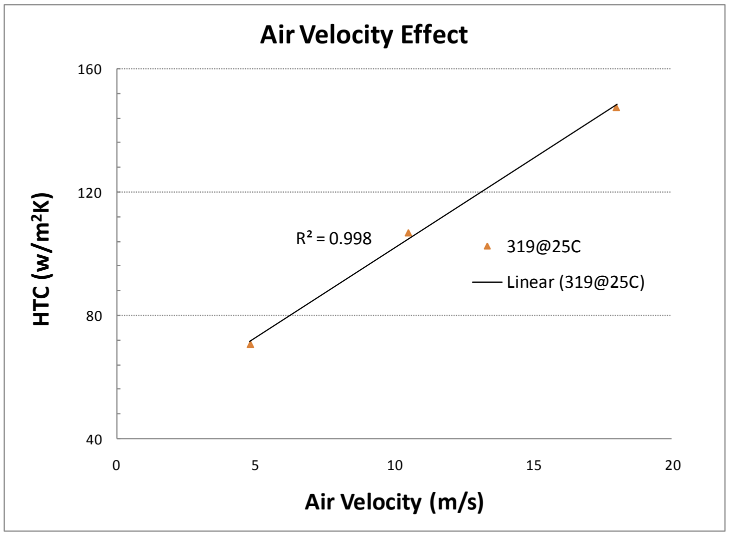

Fig. 4 Air velocity effect on HTC

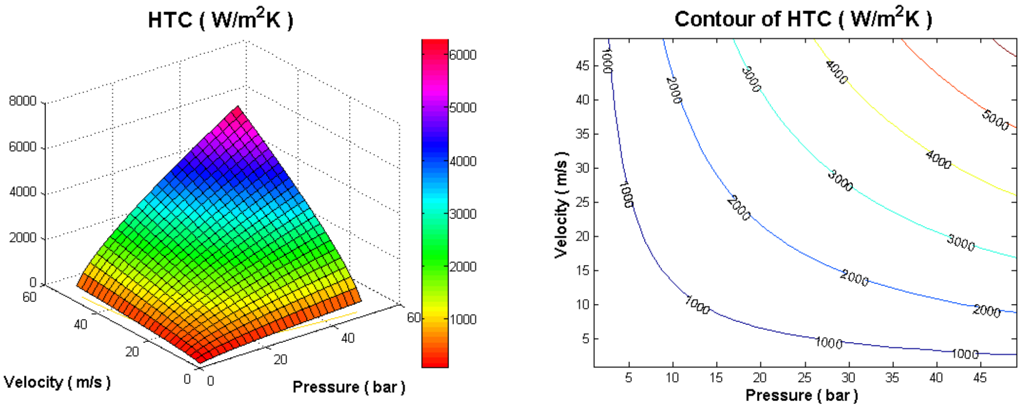

Fig. 5 a).HTC vs. hydrogen pressure and velocity b). Contour of HTC vs. hydrogen pressure and velocity[17]

4.2. Air/gas pressure effect

Thermal conductivity, specific heat and viscosity of hydrogen vary slightly with respect to pressure for the range from 1bar to 30 bars, and the density increases proportionally to pressure, in agreement with ideal gas law [18-20]. For simplicity, it is assumed in the HTC calculation that thermal conductivity, specific heat and viscosity are independent of gas pressure and velocity and the density variation is computed by the ideal gas law. With the physical properties of hydrogen and Equation 7, the HTCs at different pressures and velocities are calculated and shown in Figure 5. From these figures and Equation 6, it is apparent that HTC increases significantly with respect to gas pressure and velocity. [17]

4.3. Gas mixture effect

It is also pointed out and verified by experiments that HTC of two-component gas mixture might be bigger than the two pure components [15, 21-26]. Figure 6 shows one example for nitrogen-hydrogen mixture [21, 24]. In this figure, the HTC of the mixture reaches the highest value when the volume fraction of hydrogen is in the range from 75% and 85%.

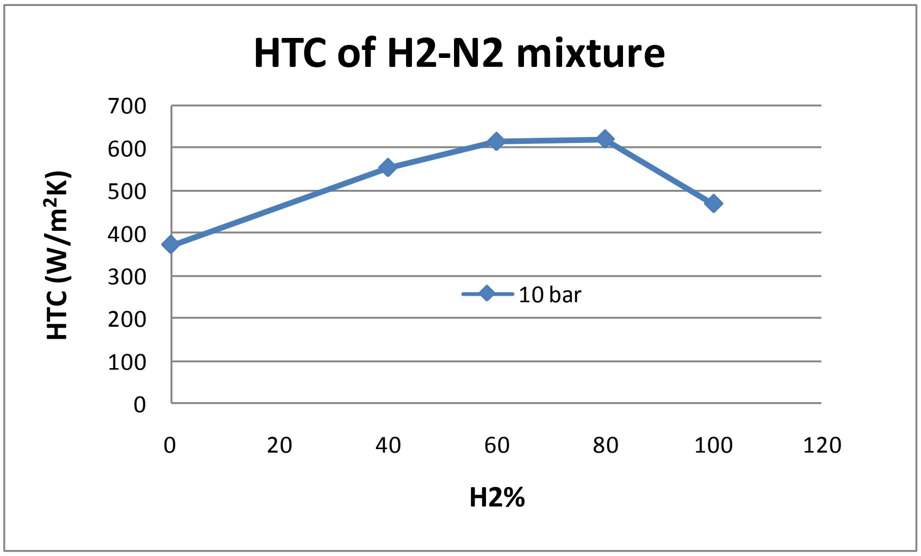

Fig. 6 HTC of nitrogen-hydrogen mixture [21]

4.4. Part orientation effect

The probe was cooled down in the forced air flow (15°C and 31-33 % relative humidity) at three orientations as shown in Figure 7. The corresponding HTC data 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. It should be pointed out that with this experimental method, the HTC is assumed uniform in space. But in production reality, local HTC data at different points vary with respect to local fluid flow (e.g. pressure, velocity, etc). As a result, HTC data vary with respect to part orientation.

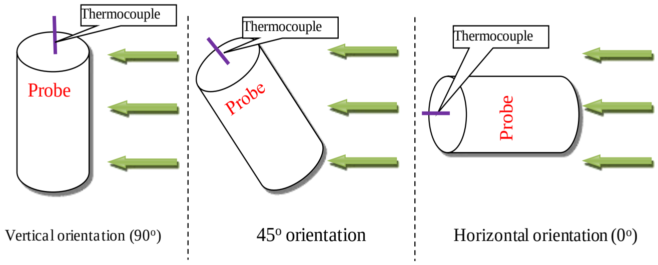

Fig. 7 Schematic of three quenching orientations

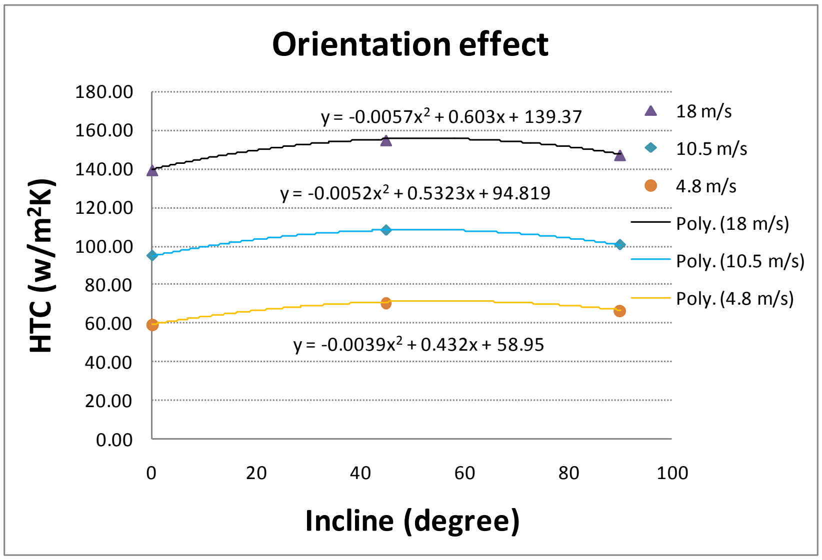

Fig. 8 Effect of quenching orientation on HTCs of cast aluminum alloy probe quenched under forced air at 15°C and 31-33 %

4.5. Air/gas temperature effect

Air temperature effect is studied by carrying out experiments at air temperatures of 15 °C and 25 °C and 3 different air velocities of 18, 10.5 and 4.8 m/s. For the air temperatures tested in this paper, no significant influence of air temperature on HTCs was found, which is similar to the results reported by Still et al. [27].

4.6. Air humidity effect

The effect of air relative humidity on HTC for cast aluminum alloy probe was studied at 15 °C and 3 different air velocities of 18, 10.5 and 4.8 m/s. Similar to air temperature, the influence of air humidity on HTC is also marginal (less than 6 %), which again is in agreement with Still et al's results [27].

4.7. Other effects

It was reported that a thin layer of surface oxides enhances the cooling rate by providing more nucleation sites for the bubble formation in the case of oil quenching, but the low conductivity of a thick layer of iron oxides leads to a decreased HTC [11]. The surface roughness affects the bubble nucleation in oil quenching considerably [14], but has little effects in air/gas quenching. It was reported that the probe material affected HTC to some degree, especially when the probe temperature is high [28].

5. Conclusions

This paper studies various influencing factors such as air/gas pressure, velocity, temperature, mixture, part orientation, material, surface roughness and oxide. It was found that the HTC increases significantly with air/gas velocity and pressure. The part orientation also affects local HTC considerably. The air humidity and air/gas temperature have little effects on HTC. Some gas mixtures with proper percentages can produce higher HTC than pure gases. Some other factors such as material, surface roughness and oxide can affect HTC to some degree in air/gas quenching.

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