Experimental analysis of wetting delay during jet impingement quenching of high temperature brass block

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Abstract

A model for the prediction of the wetting delay through jet impingement quenching of a high temperature brass block has been carried out in this study. The liquids used for jet impingement on the brass surface are water and emulsion of cutting oil (used in machine shop) and water at a proportion of 1:20. The varying parameters used for the analysis are different velocities of jet (3m/s, 5m/s, 10m/s) and initial block temperature from 250 °C to 450 °C at an interval of 50 °C. The wetting delay and wetting front propagation varied for different test conditions. When a liquid jet was impinged on the heated surface of the brass block, the jet remains stagnant up to a small region and the surface temperature decreases very slowly with time. After a certain interval, the surface temperature decreases at faster rate and the wetting front starts to move in the radial direction. The time that passes during the stagnant period of the wetting front is the wetting delay. The wetting delay in case of emulsion of cutting fluid is much higher as compared to water. The evidence was clear for wetting delay measurement for water from graphical analysis but for the emulsion it is not as evident as in many cases the temperature drops linearly with time and the wetting delay can’t be actuated exactly. The water wave front propagates throughout the surface but in case of the emulsion the wetting front does not even cover half of the total metal surface after a long interval of time. The effect of different experimental parameters on the wetting delay is also observed in the present study. The characteristics of the wetting delay are influenced by jet velocity and initial block temperature. For higher jet velocity and lower initial block temperature wetting delay decreases.

Keywords: Wetting delay; quenching; emulsion

Nomenclature

| Symbol | Description |
|--------|-------------|
| d      | Jet Diameter (mm) |
| CHF    | Critical Heat Flux (W/m²) |
| LFD    | Leiden frost point |
| t*     | Resident time (sec) |
| T_i    | Initial Block Temperature (°C) |
| V      | Jet Velocity (m/s) |
| T_w    | Surface temperature (°C) |

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1. Introduction

The rapid cooling of high temperature metal surface is generally called quenching or rewetting process, which is one of the most important processes of heat treatment. Quenching is widely used and has been extensively studied for controlling the mechanical and metallurgical properties of materials in the manufacturing industry. Among the various quenching techniques, jet impingement quenching has been proved to be an effective cooling option over the past few years due to rapid cooling and better control of high temperatures. When a liquid jet is impinged on the heated surface of the metal block, the surface is not immediately wetted by the liquid jet. The liquid jet remains stagnant up to a small region for a certain amount of time which may vary with the experimental conditions and the metal block we are using. At that time, the surface temperature decreases slowly almost at a constant rate. There is a sudden drop of temperature at the very beginning of jet impingement due to transient effect. After a certain amount of time the wave front of the jet begins to propagate on the whole surface. The delay of time when the wave front of jet remains stagnant on a small region of the surface is called wetting delay.

![Cooling curve during quenching](image)

Researchers and scientists have carried out analytical and experimental investigations for clear understanding of quenching phenomena. Chan and Banerjee [1] defined that the rewetting is the re-establishment of continuous liquid contact with a hot dry surface. Nelson [2] defined quenching as the rewetting process for establishing direct liquid-solid contact where the surface initial temperature exceeds the rewetting temperature. The rewetting temperature was represented by the Leiden frost temperature (LDF) of liquid nitrogen on copper surface. The quenching by jet impingement using water as the liquid is a very effective cooling process for high temperature surfaces. Piggott et al. [3] experimentally investigated wetting delay during cooling of a hot rod using a sub cooled water jet. It is the delay of the wave front of the liquid to spread from a stagnant zone to the entire surface of the block. The time till when the wave front remains in a stagnant zone is called the resident time.

Mozumder et al. [4-6] conducted the experimental investigations during quenching of three different cylindrical blocks i.e. steel, brass, cast iron using a sub cooled water jet. The jet was impinged from the bottom at the center of the surface of the block. They defined resident time as the period required for the wetting front to expand beyond the stagnant zone which is close to the center.

The present study is of experimental type that is performed to understand the characteristics of wetting front and resident time during quenching of a high temperature cylindrical brass block with water and emulsion jet at atmospheric pressure. The temperature is measured inside the block at a specific depth of 2mm from the hot surface. The movement of wetting front over the heated block surface is observed and the wetting delay between water and emulsion jet is compared by graphical analysis and visual observation.

2. Experimental setup and procedure

The experimental setup consists of four major parts: a structure to support the test block, a heater to heat the block, the liquid circulation system and the temperature measuring system. The other requirement was to make proper insulation to
avoid heat losses. Fig. 2 shows a schematic diagram of the experimental setup that was used during our experiment. The total setup consist of water tank, pump, pipe, reducer, valves, nozzle, cylindrical steel block, insulation, gasket, variac, thermocouple, digital panel meter etc.

![Schematic diagram of the experimental set up](image)

**Fig. 2. Schematic diagram of the experimental set up**

The experiment is started with filling up the reservoir up to a certain level with the fluid. In case of cutting fluid the emulsion of water and oil was first made and then poured into the reservoir. Then the pump was switched on and a jet of fluid is initiated through a nozzle of 1 mm diameter, which is placed centrally 23 mm from the test surface. The different velocities were obtained by regulating the bypass gate valve. The jet velocity is then calculated by bucket and weight method. A shutter is mounted in front of the nozzle to prevent fluid from striking the block prematurely. The block is heated to the desired initial temperature by heating it with an electrical heater mounted around the block. After setting all initial conditions of the experiment, the shutter is opened for allowing the jet to strike at the center of the test surface of the heated block. The camera is employed to record flow pattern over the heated block surface.

The k type thermocouple measures the temperature inside the block and at the same time, time is recorded by a stop watch. The whole procedure is repeated for various jet velocity and initial block temperature. The experiment has been conducted under various test conditions for the purpose of clear understanding of the heat transfer characteristics during jet impingement quenching of hot brass block. The jet velocity and initial temperature of the brass block are varied.

| Initial temperature of block, \( T_i \) (°C) | Jet Diameter, \( d \) (mm) | Jet velocity, \( V \) (m/s) |
|---------------------------------------------|-----------------|-----------------|
| 250, 300, 350, 400, 450                    | 1               | 3, 5, 10        |

**3. Results and discussion**

Experimental resident time has been investigated as a function of test surface temperature for metal surfaces, two different liquid and three different jet velocities. A numerous number of graphs have been found for different conditions. In this study, the resident time has been estimated on the basis of two independent ways, one is from the temperature vs. time curve and the other is from the video images. In most of the cases both agreed well. Since video recording was not made for every case, only the first mean was sometimes employed to estimate the resident time. The pattern of the wave propagation is observed during the experiment closely. One of the most important objectives of the present study is to compare the wetting delay and wetting front propagation of water and emulsion. The comparison is made by both graphical analysis and visual observation.
3.1 Comparison with graphical analysis

Graphical Analysis can be shown by Cooling curve i.e. Temperature vs. Time curve. Cooling curve for water represents ideal behavior and wetting delay can be observed in most of the cases. On the other hand, cooling curve for cutting fluid is nearly linear and it is difficult to obtain exact wetting delay from cooling curve. Wetting delay for most of the cases is found by visual observation.

![Graph showing comparison of surface temperature and time curve](image)

From the graph we can see that the resident time for cutting fluid is 26.13 seconds which is much less than the resident time of water which is 48 seconds. We can also see the temperature at which the temperature remains quite constant is pretty high for cutting fluid as compared to water.

3.2 Comparison by visual observation

In addition to graphical analysis, Visual observation is a good indication of wetting delay. Since the specific heat of water is more than that of cutting fluid, wetting front for water propagate faster & wetting delay is less compared to cutting fluid. At $T_i = 350^\circ$ C, and $V = 5$ m/s, Wetting delay for water & cutting fluid was found as 35 and 62 second respectively.

![Initial impact of jet at Ti = 350°C & V = 5 m/s](image)

3.3 Effect of different parameters on wetting delay

The effect of different parameters on wetting delay plays an important role in analysis of quenching process. The most important parameters are the jet velocity and the initial block temperature. The wetting delay varies with these parameters through a direct relationship.
3.3.1 Effect of jet velocity

Generally the higher the velocity the smaller should be the wetting delay. Because the higher velocity will remove the heat quickly from the heated surface. Therefore the wetting delay will be less. In this study we got these relationship between the jet velocity and wetting delay for most of the cases with pure water except some variations. But in case of emulsion as the temperature was decreasing linearly it was difficult to find out the wetting delay and therefore the direct relationship between the wetting delay and the jet velocity did not make out for most cases. In Fig. 5a for $T_i = 300^\circ$C, resident time in case of water for $V = 3\ m/s$, $5\ m/s$ and $10\ m/s$ has been plotted respectively. So from this figure it is evident that with the increase of velocity wetting delay decreases.

With cutting fluid we got similar result for initial temp. $250^\circ$C, $300^\circ$C, $400^\circ$C and $450^\circ$C. But in these cases the wetting delay could not be determined for some velocities. Fig. 5b shows the variation in wetting delay at different jet velocities for $T_i = 250^\circ$C. For this case we also get a good indication of the direct relation between wetting delay and jet velocity. Thus we can say that the wetting delay decreases with the increase of jet velocity.

3.3.2 Effect of initial block temperature

The initial temperature of the test block is also influential in terms of wetting delay. Generally the highly heated block will take more time to become cool. So, the wetting delay should be higher. In our present study we got almost similar results for most of the cases. Although in some cases the wetting delay could not be exactly found. The wetting delay for different initial block temperature with different velocities have been plotted in this section for both water and cutting fluid. The wetting delay for water at different initial block temperatures for $V=3\ m/s$ is shown in the Fig. 6a. From this figure we see that with the increase of initial block temperature, wetting delay increases except for $250^\circ$C.
In case of cutting fluid the relationship between the wetting delay and the initial block temperature is not as clear as water. The wetting delay for cutting fluid at different initial block temperatures for \( V = 10 \text{ m/s} \) also shows similar results as shown in Fig. 6b. Thus we can say that the relationship between wetting delay and initial block temperature was almost similar in all the cases except some variations.

4. Conclusions

The study has focused on the wetting delay parameter which is very important in investigating the underlying mechanisms of quenching process. Therefore, from the observations of the movement of wetting front and wetting delay the following conclusions can be drawn:

1. The wetting delay for brass block during jet impingement of water was very significant and easily identified in most of the cases. But in some cases we could not clearly identify the wetting delay.

2. The wetting delay during jet impingement of cutting fluid was not as clear as water though in some cases we got good indication of the wetting delay.

3. The wetting delay in case of cutting fluid is much higher than that of water. This is due to the fact that the cutting fluid we used is a 1:20 mixture of cutting oil (used in machine shop) and water. So the thermal conductivity of water was decreased as well as the heat removal rate.

4. In case of cutting fluid the wetting front took a long time to propagate and in some cases with lower velocities the whole surface could not be wetted by the jet. This is because the surface becomes oily just after the jet strikes the block which resist the front to propagate.

5. The resident time of wetting front increases with increasing initial temperature and with decreasing jet velocity. The higher velocity removes the heat quickly from the heated surface and therefore the wetting delay is less.

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