Experimental study of quenching process on a rotating hollow cylinder by one row of impinging jets

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Abstract. Quenching cooling rate of rotary hollow cylinder by one row of water impinging jets has been experimentally studied. Water jets ($d = 8$ mm) with sub-cooling 55 to 85 °C and Reynolds number 8,006 to 36,738 impinged over rotary hot hollow cylinder (rotation speed 10 to 70 rpm) with initial temperature 250 to 600 °C. Impingement impact angle of row of jets varied between 0 to 135° and jet-to-jet spacing in row pattern was 2 to 8d. The results revealed more uniformity on cooling rate of quenching in smaller jet-to-jet spacing (2 and 4d) where wetting front regions are located closer to neighbor jet’s region. By increasing spacing, footprint of annular transition region was highlighted in quenching cooling rate contour. A distinct quenching characteristic was obtained for impingement impact angle of 0° compare to other angles. With initial temperature above the Leidenfrost temperature, low cooling rate was achieved in film and transition boiling compare to a steep increase of cooling rate at start of quenching with higher maximum heat transfer for experiments with initial temperatures less than Leidenfrost temperature. The effect of other parameters on quenching cooling rate was highlighted in film and transition boiling while no significant differences were observed in nucleate boiling.

Keywords: Experimental study, Multiple impinging jets, Rotating surface, Quenching, Transient boiling

1. INTRODUCTION

The ongoing trend towards greater functionality, more controlled properties and speed in manufacturing processing results in a demand for more advanced thermal management of steel products. In the steel industry, production lines continuously convey different steel products such as tube, rod, plate and profile over milling machines with or without forced cooling systems that reduce temperature level of profiles during transformation. Among different cooling techniques, water impinging jet is one of the most effective, fast-quenching systems. There has been great interest in heat transfer experimental study of quenching by water jet and many of the reported studies have focused on a single water jet quenching a stationary test sample. Karwa et al. (2012) reported three distinct regions of quenching process on a flat surface with single water jet: circular wetted region surrounding impingement stagnation point, annular transition zone and unwetted region in the outer layer. Woodfield et al. (2009) studied boiling region of a single water jet over a stator flat surface. They investigated effect of initial surface temperature, test specimen material, water sub-cooling and jet velocity on the size of boiling regime and shown higher water sub-cooling and velocity decreased width of wetted region while greater material thermal conductivity widened the wetted region. In a research study of steady state and transient quenching of horizontal surface by single water jet, Agrawal et al. (2012) investigated effect of nozzle diameter on rewetting temperature and velocity and also reported a list of previous experimental studies that carried out with a single round water jet. Effectiveness of maximum heat flux by parameters of water impingement and quenching system was studied by Mozumder et al. (2006) in case of single water jet impinging jet.

In considering quenching surface movement and curvature, there are few studies that investigate influence of quenching heat transfer by these two important parameters on tube milling machine in addition to other parameters. Mozumder et al. (2014) performed quenching of a rotary cylinder at 460-560 °C with a single round water jet, analyzed quenching hydrodynamic phenomena, and reported effect of rotation on variation of temperature and heat flux after each cylinder’s revolution. Gradeck et al. (2009) conducted experiments on quenching of a stationary and rotary cylinder by impinging planar water jet and reported lower critical heat flux value on the rotating surface of test specimen and variation of maximum heat transfer’s location over the surface during quenching. Gradeck et al. (2011) compared their experimental result of heat flux of a rotating cylinder with some of available heat flux correlations for a static surface and shown over estimation of heat flux by using the correlations for a moving surface quenching. They also studied effect of planar jet velocity, rotation speed, sub-cooling and nozzle distance on critical heat flux.

Among the literature studied by the authors, no experimental study was found to study the effect of multiple impinging jet configuration on quenching of a rotating hot convex surface. The objective of the present study is to investigate experimentally quenching cooling rate of a rotary hot hollow cylinder with one row of water impinging jets. The research will cover study of effect of jet-to-jet spacing, Reynolds number, impingement impact angle, sub-cooling temperature, initial sample temperature and rotation speed of the test specimen on the quenching heat transfer.
2. Experimental methodology

The schematic of the experimental setup is shown in Fig. 1. The test specimen is a hollow cylinder carbon steel with outer diameter of 152 mm. In order to measure time depended temperature of quenching, N-type thermocouple was used at two different depths of the test specimen’s thickness: \( r_1 \) and \( r_2 \). Each thermocouple was mounted in a drilled hole \((d_{\text{hole}} = 1.5 \text{mm})\) carefully to reduce contact resistance at the measurement point and especial cement was used to fix the thermocouple position inside the hole to be ensure that there is a stable contact between tip of the sensor and bottom of the hole during heating and cooling processes. One slip-ring was mounted at end of the rotary shaft to avoid twisting of thermocouples’ wire. The DAQ system contained a data logger to collect signals from instruments and send them to computer. LabVIEW program was used to monitor and control experimental process and record measurement signals from the DAQ system.

![Schematic of experimental setup](image)

The experimental process of each test contained three main steps. In the first step, temperature of water in the tank was regulated by a cooling and heating system and a pump circulated the water through the piping system. The water volume flow rate was measured by a magnetic flow meter and relative pressure was monitored by pressure difference transducer. In the second step, an induction heater heated the rotating test specimen slightly over the initial temperature and was taken away from test chamber. Finally, quenching process was started at the desired initial temperature of quenching, defined in the monitoring system, by sending voltage signal to solenoid valves to switch direction of water circulation towards the impinging jets inside test chamber.

In this experimental study, 20 tests carried out and effect of several parameters was studied on quenching cooling rate of the rotary cylinder with one row of round water jets (diameter, \( d = 8 \text{ mm} \)); rotation speed of sample \((w = 10 \text{ to } 70 \text{ rpm})\), initial temperature of sample \((T_i = 250 \text{ to } 600 \degree C)\), impinging jets’ Reynolds number \((Re = 8006 \text{ to } 36,738)\), sub-cooling temperature \((\Delta T_{\text{sub}} = 30 \text{ to } 85 \degree C)\), jet-to-jet spacing \((S/d = 2 \text{ to } 8)\) and impinging impact angle \((\theta = 0 \text{ to } 135 \degree)\). Jet to wall distance \((H)\) and impinging angular position \((\text{impinging’s inclination})\) were constant in this study. In order to obtain accurate uncertainty calculation, four thermocouples were calibrated by the manufacturer from 20 to 800 \degree C. The maximum uncertainty of thermocouple sensor and data acquisition system was \(\pm 1.1 \%\) at temperature of 100 \degree C. The uncertainty of thermocouple sensor location, water flow rate and water temperature were \(\pm 4.6\), \(\pm 1.8\) and \(\pm 4.8 \%\), respectively.

3. Results and discussion

In this section, effect of some parameters on cooling rate of the quenching system is discussed. Figure 2(b) plots temperature drop of two axial points in the two measurement depths in an experiment with \(Re = 8,006, S/d = 4, \Delta T_{\text{sub}} = 75 \degree C, w = 50 \text{ rpm} \text{ and } \theta = 90 \degree C\). The result shows the nearly same temperature drop rate at \(x/d = 2\) and \(4\) in measurement line \(r_2\). There is also a delay that temperature drops in line \(r_1\) which is due to heat conduction through the test specimen material. Another way to compare different configuration of quenching tests is to analyze cooling rate of measurement points close to quenching surface \((4 \text{ mm} \text{ beneath the surface})\). Figure 2(c) presents calculated cooling rate at points \(a\) and \(c\). Cooling rate after one revolution \((dT/dt)\) is defined in each measurement point according to Eq. (1), where \(n\) determines revolution number, \(dT\) is temperature difference in the measurement point after one revolution and

\[
\frac{dT}{dt} = \frac{T(t) - T_{\text{ambient}}}{t}
\]
\( dt \) is defined as the time required for the measurement point to pass the stagnation point and reach it again after one revolution.

\[
dT_n/dt = (T_{n+1} - T_n)/(t_{n+1} - t_n), \quad n = 1, 2, 3, ...
\]  

(1)

In agreement with the result in Fig. 2(b), very similar cooling rate trend is observed in Fig. 2(c) for two measurement points, but more detail is observed from cooling rate graph. In cooling graphs, dots represents the moment which measurement point is in stagnation point of water jet. Figure 2(c) reveals slightly higher cooling rate at beginning of quenching in film boiling regime. After the first peak value, wetting front region tends to widen and stagnation point experiences boiling in film boiling regime. Then there is a minimum cooling rate which is known as Leidenfrost temperature (350 \( ^\circ \text{C} \) in this experiment) and it is located between film and transition boiling regime. Cooling rate is increased in transition regime up to a peak value which nucleate boiling is highlighted and the maximum heat transfer is CHF (critical heat flux) point. In the analysis process, similar trend of temperature drop was captured in the measurement points of line \( r_1 \) and \( r_2 \) for all experiments that spacing between jets was constant (\( S/d = 4d \)). Therefore graphs of these experiments present temperature measurement close to impingement surface in point \( a \) and effect of jet-to-jet spacing along the line \( r_2 \) is discussed distinctly.

3.1 Effect of Reynolds number

Jet velocity is one of the parameters with substantial impact on heat transfer rate and its effect is plotted in Fig. 3(a) and Fig. 3(b) in a series of conducted experiments (\( S/d = 4, \theta = 90^\circ, T_i = 600^\circ\text{C} \) and \( \Delta T_{\text{sub}} = 25^\circ\text{C} \)). In Re = 8,006 starting cooling rate is very low and there is a temperature range (450 - 600 \( ^\circ \text{C} \)) which cooling is in a constant rate (6 \( ^\circ \text{C}/\text{rev} \)) due to film boiling regime over the surface. Then transition boiling is achieved where Leidenfrost effect is unhighlighted and there is a balance between potential of liquid’s heat extraction and solid’s heat supply, and cooling rate increases rapidly and reaches the peak value. This trend is diminished by increasing jet velocity of impingement. For Re > 8,006 a drastic increase of temperature drop was captured above 400 \( ^\circ \text{C} \) that is also seen in cooling rate curve (Fig. 3(b)). This distinct peak of cooling rate at beginning of quenching can be due to that, in presence of surface moving during impingement, higher Re improves potential of liquid’s heat extraction from hot solid surface by providing better contact between the liquid and surface in film and transition boiling regimes and maximum cooling rate is achieved at film...
boiling. Quenching’s heat transfer improvement by higher Re is very significant that Leidenfrost effect is diminished and better cooling rate is obtained at 300 - 400°C for Re = 36,738 and 26,686 compare to the peak value for Re = 8,006. In agreement with Robidou et al. (2002) that studied single water jet, Re variation has no impact on cooling rate of nucleate boiling regime in a row of water impinging jets.

![Figure 3: (a) Recorded temperature at point a influenced by Re (b) cooling rate at point a effected by Re variation (c) effect of ∆T_sub on temperature drop of quenching (point a) (d) influence of ∆T_sub on cooling rate at point a.](image)

3.2 Effect of sub-cooling

Subcooling temperature can be available in a wide range in different industry and it is important to understand its influence on the quenching system by multiple arrangement of jets (one row of nozzles). Figure 3(c) and 3(d) represents result of experiments with Re = 16,012, S/d = 4, θ = 90° and Ti = 600°C and reveals similar trend of cooling rate for 55 ≤ ∆T_sub ≤ 65°C and with an improvement for 75 ≤ ∆T_sub ≤ 85°C in film boiling. The improvement of cooling rate highlights effect of higher sub-cooling and can also be seen in transition boiling regime for 75 ≤ ∆T_sub ≤ 85°C. Leidenfrost temperature is increased with sub-cooling (except ∆T_sub = 75°C) for the configuration of the row of water jets which is in agreement with reported result of single water jet by Gradeck et al. (2009). Second peak is obtained in higher temperature only with the highest sub-cooling and it is also clear that for different sub-cooling, the cooling rate trend is the nearly same below 300°C in nucleate boiling.

3.3 Effect of impingement impact angle

Schematic of studied impact angles of the row of impinging jets versus rotation direction are illustrated in Fig. 4(b). The impact angle is defined as angle between impingement axis (dash line) and y-axis. The result shows distinct trend of temperature drop and cooling rate at θ = 0°. Gravity force is overcome on impingement flow in this impact angle. Vertical position of wetting front and surface movement weaken the potential of suitable contact between liquid flow
and solid surface. Therefore low cooling rate is obtained at beginning of quenching and no peak value is observed at about 300°C. Greater impact angle leads to a drastic increase of cooling rate in film boiling regime. At $\theta = 45$ and 135°, effect of gravity is less dominated and Leidenfrost temperature is shifted to higher temperature. A visualization investigation revealed that at configuration of $\theta = 45°$, moving surface carries a part of wetting front flow in downstream of impingement region up to $\theta = 180°$ in dry zone which is an advantage gained from this particular position of row of water jets versus rotation direction. At impact angle of 135°, slightly lower cooling rate is seen in transition boiling while in this impact angle gravity force and rotation direction can weaken the potential of proper contact between the water jets and moving surface. Impact angle of 90° increases cooling rate in the film boiling compare to other tested impact angles. Lower heat transfer rate in transition boiling and better result in nucleate boiling are achieved with this impact angle of impinging jets.

![Figure 4](image)

Figure 4: (a) temperature at point $a$ influenced by impinging impact angle, $\theta$ (b) cooling rate at point $a$ influenced by $\theta$ variation (c) quenching effectiveness by $S/d$ (point $a$) (d) effect of $S/d$ on cooling rate at point $a$.

### 3.4 Effect of jet-to-jet spacing

Design of quenching system by multiple pattern of water jets defines new parameter of spacing between water impinging jets. In the case of high value of $S/d$ jet water flow is not influenced by neighbor jets’ wetting front flow and individual jets are considered as single impinging jet. On the other hand at a low value of $S/d$, wetting front flows collide each other and effect on cooling rate of neighbor jets. Spacing between jets can effect on both uniformity of cooling rate over surface and average cooling rate depending on the ratio between nozzles and surface cooling areas. In order to study effect of jet-to-jet spacing, following parameters were kept constant: $Re = 16,012$, $\Delta T_{sub} = 75°C$, $\theta = 90°$ and $w = 50 rpm$, and $S/d$ was varied between 2 to 8.

Matched temperature drop is seen for spacing 2 and 4d in the entire quenching tests and for $S/d = 6$ and 8, similar trend of temperature drop is obtained above 500°C and then up to 300°C. $S/d = 6$ provide greater temperature drop compared to $S/d = 8$, see in Fig. 4(c). Cooling rate’s graph in Fig. 4(d) reveals that smaller spacing between jets
increases the heat transfer rate in film and transition boiling regimes. By increasing spacing between the jets, there is less number of nozzles over the quenching surface; therefore, wider cooling region is considered for each individual jet. This effect can be explained as the reason for lower cooling rate for \( S/d = 6 \) and 8 while for \( S/d \leq 4 \) cooling rate remains in a considerable high level from 600 to 300 °C. For \( S/d > 4 \) minimum temperature between film and transition boiling (Leidenfrost) is shifted to higher temperature and it is hard to recognize this temperature for spacing of 2\( d \). Similar to other parameters, there was no significant effect of spacing on cooling rate in nucleate boiling regime.

In order to investigate effect of jet-to-jet spacing on heat transfer over the quenching surface, one should analyze result of quenching along the line \( r_2 \). Figure 5 represents cooling rate of all measurement points in line \( r_2 \) (\( x/d = 0 \) to 4) in different spacing setups and shows that smaller spacing \( S \) provides more uniform cooling rate along the \( x \)-axis at different temperatures. By increasing the spacing, there is a distinct peak of cooling rate around the central jet’s stagnation point (\( x/d = 2 \)) in film boiling upon first contact of liquid-solid (\( T_i > 550 \) °C), and the rate decreases due to presence of vapor film over the quenching surface and no effect of neighbor jets is observed in the cooling rate’s contour plot for spacing of 6 and 8\( d \). After a delay by resident time (Mozumder et al. (2005)), wetting front starts to move and grow over the surface while stagnation region \((1.5 < x/d < 2.5)\) reaches to \( T_i < 350 \) °C. During growth of wetting front toward dry zone, the annular transition boundary experiences boiling, therefore higher cooling rate was captured at about \( x/d = 0 \) and 4. This effect was more pronounced in larger spacings \((S/d = 6 \) and 8\)), because the wetting front region is wider before collision to neighbor jet’s wetting front.

### 3.5 Effect of rotation speed

Effect of rotation speed close to quenching surface in Fig. 6(a) shows faster temperature drop on every sample’s revolution for 10 \( rpm \) as the measurement point passes the wetting front region more slowly. In downstream of impingement region, where the measurement point is in dry zone, temperature starts to rise by heat recovery until it reaches the stag-
nation region (wetted zone) after one revolution. This phenomenon is less visible with increasing revolution speed in line \( r_2 \), 4 mm beneath the impingement surface. In the line \( r_1 \), effect of rotation cycles and the heat recovery are not captured as clearly as in line \( r_2 \), but similar trend of temperature drop is obtained for different rotation speeds by comparing to line \( r_2 \). Cooling rate graphs in Fig. 6(b) shows poor quenching in film boiling at \( \omega = 70 \) rpm that can be due to ratio of surface speed to water jet velocity is so great which potential of good contact between liquid and solid surface is weaken. It should be mentioned that rotation speed of 10 rpm provides highest cooling during every individual revolution of test specimen, but \( \omega = 50 \) rpm increases the cooling rate slightly in the entire quenching process compare to 10 rpm. In nucleate boiling no changes is captured on cooling rate for \( \omega > 10 \) rpm.

3.6 Effect of initial temperature

Initial temperature of the quenching is the parameter determines type of boiling regime over the surface in beginning of quenching, therefore it plays an important role to control maximum cooling rate of quenching. As it is shown in graphs of Fig. 6(c), slightly sharper temperature drop is captured for experiment with \( T_i < 550 \) °C which this variation is more pronounced in Fig. 6(d). In presence of vapor film at \( T_i = 550 - 600 \) °C, much lower cooling rate was obtained in film boiling and maximum cooling rate is lower compare to experiments at \( T_i < 550 \) °C. The maximum cooling rate increases by decreasing initial temperature in film and transition boiling and decreases after CHF position in nucleate boiling. Quenching at \( T_i \geq 550 \) °C results maximum cooling rate at about \( T = 310 \) °C (CHF temperature). It is found that quenching initial temperature closer to Leidenfrost provides higher maximum heat transfer and the result shows best cooling rate beneath the surface is achieved in the case of \( T_i = 350 \) °C. It is notable that nearly same peak value of cooling is captured in case of \( T_i = 450 \) °C in transition and \( T_i = 250 \) °C in nucleate boiling regimes.
4. CONCLUSIONS

Quenching a rotary hollow cylinder with water impinging jet is a complex heat transfer mechanism with distinct pattern of heat flux variation in different boiling regimes effected by quenching parameters. Besides the previous research studies on quenching by single water impinging jet, for the first time, experimental study of quenching a rotary hollow cylinder by multiple water jets (one row of nozzles) was carried out in a controlled measurement setup. Effect of Re, subcooling temperature, impingement impact angle and jet-to-jet spacing as liquid jets parameters were investigated as well as solid test specimen parameters (rotation speed and initial temperature). The result revealed each parameter influences the heat transfer differently on film and transition regimes while no significant changes in cooling rate was captured in nucleate boiling regime with parameters’ variation, except initial quenching temperature that effected the result.

Reynolds number provided great improvement on cooling rate of film and transition boiling regimes which are known with low heat transfer rates. Quenching cooling rate increased with higher subcooling in film and transition boiling as well as in CHF temperature. A distinct heat transfer trend was achieved for impinging impact angle of $\theta = 0^\circ$ where gravity force effects water impingement flow and weaken potential of suitable contact between liquid and solid surface. Analysis of jet-to-jet spacing revealed that spacing between 2 to 4$d$ provides more uniform cooling rate with greater magnitude over the wetting front of each individual water jet compare to $4 < S/d \leq 8$. The cooling rate uniformity was also observed in both film and transition boiling regimes.

High rotation speed $\omega = 70 \text{ rpm}$ reduces interaction time between water jet and moving surface which results low cooling rate in film boiling. Temperature variation on every revolution was highlighted in low rotation speeds ($\omega \leq 30 \text{ rpm}$) where heat transfer uniformity was improved in film and transition boiling regimes. Initial quenching temperature effected on trend and maximum cooling rate of quenching significantly. In $T_i \geq 550 \degree C$, lower maximum of heat transfer was achieved compare to experiments that quenching started at temperature close to Leidenfrost temperature at transition boiling regimes.

5. ACKNOWLEDGEMENTS

The authors acknowledge financial support by Swedish Energy Agency, Ovako Company (Hofors, Sweden) and University of Gävle (Sweden). The authors are thankful for the assistance received by personnel at the laboratory of University of Gävle, especially Mr Rickard Larsson and Dario Senkic.

6. REFERENCES


