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CARBON STEEL QUENCHING AND MAXIMUM HEAT FLUX WITH WATER JET IMPINGEMENT

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ABSTRACT

An experimental investigation of jet impingement quenching has been performed for three different block materials copper, brass and steel with jet velocities of 3-15 m/s, jet subcoolings of 5-80K and initial block temperatures of 250-600 ºC. The present study has focused to investigate the characteristics of quenching for carbon steel only. The effect of experimental parameters on the maximum heat flux (the maximum value of heat flux from the solid and carried out by the liquid) was investigated in the present study. The value of maximum heat flux increases with the jet velocity and also with liquid subcooling. The maximum heat flux is also found to be almost independent of block initial temperature. A correlation of maximum heat flux for carbon steel together with the dominating parameters is proposed here which well agrees with the experimental data.

Keywords: Quenching, Jet Impingement, Heat Flux

1. INTRODUCTION

Jet impingement quenching is widely employed in many industrial applications relating to rapid cooling and better control of high temperatures. In the manufacturing world, jet cooling is used in processes such as extrusion, casting, forging and annealing for the purpose of having precise mechanical and metallurgical properties.

Many experimental and analytical works on quenching phenomena have been studied during the last few decades. The quenching process has been defined by researchers in many ways [1]. Chan et al. [2] defined the rewetting as the re-establishment of continuous liquid contact with a hot dry surface. They found that rewetting always occur when the temperature of the hot surface is below a certain value generally referred as the rewetting, sputtering or Leidenfrost temperature.

The quenching by water jet impingement is revealed as a rapid cooling process for high temperature surfaces. The heat transfer rate is significantly greater than other conventional cooling methods. Wolf et al. [3] reported that for single phase convection, the heat transfer coefficient for water jet impingement cooling exceeds 10kW/m^2. For this reason, the cooling by impinging jets is preferred in many industrial applications.

Filipovic et al. [4] conducted transient boiling experiments where a large preheated specimen was quenched by a water wall jet on its top surface. They observed the propagation of the quench front in the direction of flow along the surface. They reported that the nucleate boiling or single phase convection was present in the upstream of the quench front while the film boiling was occurred in the downstream of the front.

Mozumder et. al [5-7] conducted the experimental investigations of quenching for three different cylindrical blocks i.e. steel, brass and cast iron using a sub cooled water jet. They observed that the wetting front becomes stagnant for a certain period of time in a small central region before wetting the entire surface and defined this time as the resident time.

2. EXPERIMENTAL

The experiment was actually performed by Mozumder [5] and the detailed descriptions of the experiment can be found on there. Different elements of the experimental setup are also shown in Fig.1.

2.1 Experimental Setup

The experiment [5] was conducted individually for three different materials of copper, brass and steel. The similar behaviors were found for copper and brass block while bit dissimilarity was found for steel. In this research work, the experimental data was taken from the experiment [5] where a hot cylindrical steel block was quenched by water jet impingement. A water jet of 2 mm was stroked at the center of the heated surface. The temperature readings from the thermocouples recorded by the data acquisition system were used to get the surface parameters i.e. surface temperature and surface heat flux of the heated block. A high speed video camera was used to capture the flow phenomena during quenching. Some video images were available to observe these flow phenomena for this study.

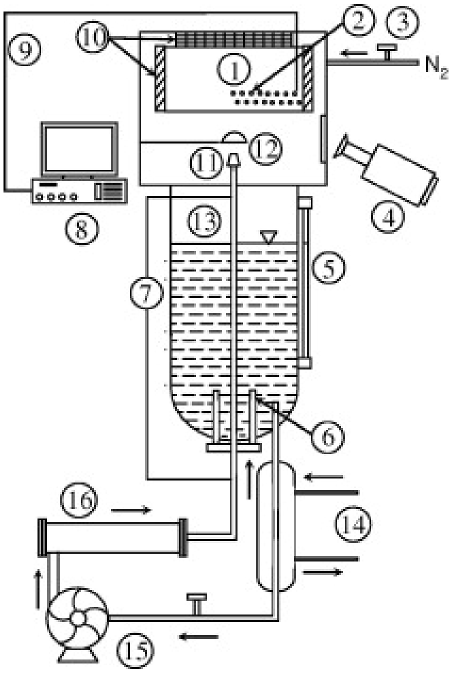

Fig 1. Schematic diagram of the experimental set-up

1 – tested block, 2 – thermocouple positions, 3 – nitrogen gas valve, 4 – high-speed video camera, 5 – level gauge, 6 – main heater, 7 – dynamic strain meter (for measuring jet velocity), 8 – data acquisition system, 9 – thermocouple wire, 10 – block heaters, 11 – nozzle, 12 – rotary shutter, 13 – liquid tank, 14 – cooler, 15 – pump, and 16 – auxiliary heater

The present study focuses to investigate the maximum heat flux during quenching of carbon steel block under the same experimental conditions as for copper and brass block.

2.2 Analysis of Temperature Data

During quenching of hot surfaces the direct measurement of surface heat flux and temperature is very difficult. It is impossible to get the thermal history directly just from the surface at which the jet is impinged without greatly disturbing the flow and boiling phenomena. An inverse heat conduction technique [8] is proved to get the surface heat flux and temperature from knowing the history of temperatures inside the hot solid surface.

3. RESULTS AND DISCUSSION

The effects of dominating parameters have been analyzed in this section. The variation of Maximum Heat Flux (MHF) with radial position, jet velocity, jet subcooling, block initial temperature and with block material are discussed here.

3.1 Effect of Radial Position on MHF

The value of maximum heat flux changes with the radial position of the jet impinged point. The solid-liquid interaction region remained fixed up to the radial position of 8±3 mm for most of the cases and then the wetting front started to move in the radial direction.

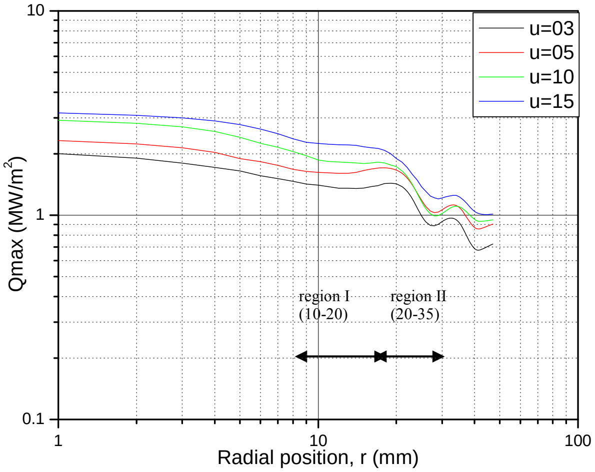

Fig 2. Variation of maximum heat flux with radial position for different jet velocity (T_b=300°C, ΔT_{sub}=20K)

The heat flux decreases very slowly within this region (Fig.2). In this analysis, the variation of maximum heat flux for these regions has been considered when the wetting front started to move. Two distinctive regions are identified: region I (from 10-20 mm) and region II (from 20-35 mm). In the region I, the maximum heat flux decreases slowly with the radial position. In the region II, the maximum heat flux decreases more rapidly with radial position. It was observed that the area of vigorous boiling region increased when the wetting front started to move outward in the radial direction. The available surface area to become cool is increased and the heat carrying capacity of coolant is decreased when it moves outward in the radial direction. This results in decrease of maximum heat flux with increasing radial position.

3.2 Effect of Jet Velocity on Maximum Heat Flux

The effect of jet velocity on maximum heat flux is shown in Fig.3. Maximum heat flux increases with the jet velocity. Maximum heat flux is higher for a smaller

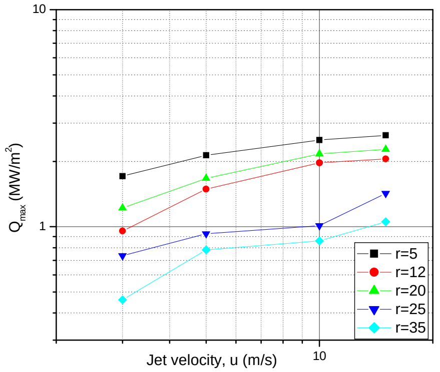

Fig 3. Effect of jet velocity on maximum heat flux (T_b=400°C, ΔT_{sub}=20K)

radial position for a particular jet velocity which also indicates the maximum heat flux decreases with the radial position. The higher jet velocity means the higher flow rate of coolant supplied to the heated surface which has direct effect on the rate of heat transfer.

3.3 Effect of Sub-Cooling on MHF

The variation of maximum heat flux with subcooling of water for different radial position is presented in Fig.4. Higher subcooling means the higher temperature difference between the saturation temperature and liquid temperature. The lower temperature liquid takes more heat from the heated surface to reach its saturation temperature. Therefore the rate of heat transfer is increased. This observation has been found for all experimental conditions.

3.4 Effect of Initial Block Temperature on MHF

Mozumder [5] found that the effect of initial block temperature on maximum heat flux is very small. The required time to reach its maximum heat flux point is longer for higher initial temperature. Due to its very small effect it is considered that maximum heat flux is almost independent of block initial temperature T_b. Figure 5 shows the effect of initial temperature on the maximum heat flux for different radial position. It is also proved that there is very little effect of T_b on the maximum heat flux. We have ignored some scattering data for the initial temperatures of 450-600ºC.

3.5 Effect of Block Material on MHF

It is evident that the block material influences strongly the rate of heat transfer. Mozumder [5] experimented on jet impingement quenching of three different block materials (copper, brass and steel) and reported that the maximum heat flux for copper material is more than two times than steel material. The thermal conductivity of copper, brass and steel are 380 W/mK, 112 W/mK and 37.8 W/mK respectively. Therefore, the thermal conductivity of carbon steel is approximates 1/10 times of copper. The maximum heat flux is strongly affected by the block material. In the case of copper, the effects of impinged water quickly reached to the entire surface. The heat of the quenching area is quickly recovered by the stored heat from the nearer surface area due to its higher thermal conductivity. For steel, the surface is cooled locally near the surface at which the jet is impinged. Because of low thermal conductivity heat is locally removed from the heated surface but the total effect of cooling process does not feel immediately over the entire solid body.

3.6 Correlation of Maximum Heat Flux

The following two correlations have developed for the initial temperatures of 250-400ºC for the two distinct regions:

For region I (radial position of 10-20mm)

$$\frac{Q\max}{\rho_g h_{fg} u} = 55.119\left(\sqrt{\frac{(\rho c\lambda)_l}{(\rho c\lambda)_s}}\right)^{0.674}\left(\frac{\rho_l u^2 (2r_q - d)}{\sigma}\right)^{-0.295}(1+Ja)^{0.136}$$

For region II (radial position of 10-20mm)

$$\frac{Q\max}{\rho_g h_{fg} u} = 1.106\left(\sqrt{\frac{(\rho c\lambda)_l}{(\rho c\lambda)_s}}\right)^{-1.291}\left(\frac{\rho_l u^2 (2r_q - d)}{\sigma}\right)^{-0.287}$$

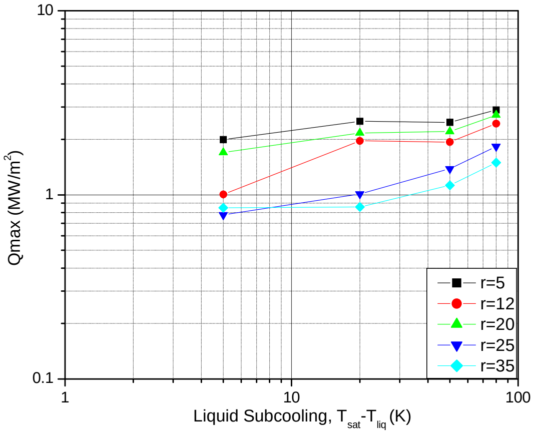

Fig 4. Variation of Maximum surface heat Flux with liquid subcooling (T_b=400°C, u=10m/s)

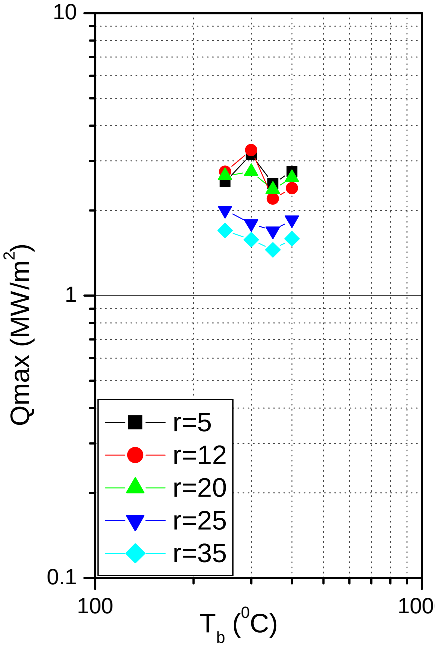

Fig 5. Effect of initial block temperature on maximum heat flux (ΔT_{sub} =50K, u=15m/s)

The coefficients of these two correlations have been determined by using least square method from the experimental data of maximum heat flux. Experimental data is then compared with these proposed correlations for the two regions. The experimental data is within ±25% and ±30% of the proposed correlations for region I and region II respectively.

4. CONCLUSION

The present study has focused on the maximum heat flux during jet impingement quenching of steel block. Maximum heat flux is one of the important parameters in investigating the underlying mechanisms of quenching process. It is a very complicated process. At present the following conclusions can be drawn:

1. The maximum heat flux always occurs during the movement of the wetting front. During this movement the position of the maximum heat flux also moves from the center towards the circumference.
2. The maximum heat flux is reported to be strong function of jet sub-cooling, jet velocity and material property although, it is independent of block initial temperature.
3. The correlations between the maximum heat flux and the important non dimensional groups have been proposed of the steel block for the two regions: region I (10-20mm) and region II (20-35mm).
4. The maximum heat flux for the initial temperatures range of 250-400ºC is well predicted within an accuracy of ±25% and ±30% for two regions I and II respectively by comparing it with the proposed correlation of maximum heat flux.

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6. NOMENCLATURE

Symbol	Meaning	Unit
d	Jet diameter	(mm)
Q_{max}	Maximum heat flux	(MW/m^2)
h_{fg}	Latent heat of vaporization	(kJ/kg)
J_a	Jackob Number	(-)
r	Position in the radial direction of the block	(mm)
r_q	Radial position at maximum heat flux point	(mm)
T_b	Initial block temperature	(°C)
T_{liq}	Liquid temperature	(°C)
T_{sat}	Saturated liquid temperature	(°C)
ΔT_{sub}	Liquid subcooling, (T_{sat} -T_{liq})	(K)
u	Jet velocity	(m/s)
c	Specific heat	(kJ/kg K)
λ	Thermal conductivity	(W/m^2 K)
ρ	Density	(kg/m^3)
σ	Surface tension	(N/m)
Subscripts		
l	liquid	
s	solid	

7. MAILING ADDRESS

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