Wetting Speed during Quenching of Hot Surface by Impinging Jet

Chitranjan Agrawal

Assistant Professor, College of Technology and Engineering, Maharana Pratap University of Agriculture and Technology, Udaipur-313001, Rajasthan, India

Abstract- **Hot Stainless Steel (SS-304) horizontal surface of different initial temperatures are cooled by water jet of 33 °C temperature and 3 mm diameter. The surface cooling performance is investigated with flow rate of 1.2 and 5.10 lpm. The test surface is of 150 mm long, 150 mm wide and 2 mm thickness. Surface is initially heated up to certain temperature in furnace and cooled by downward impinging jet. The process of surface cooling is recorded by a camera and the wetting speed over the hot surface is determined. The wetting speed on the hot surface is observed in the range of 2 – 35 mm/s for 10 mm – 40 mm spatial locations. It has been observed that the wetting speed increases with rise in flow rate and reduces for higher downstream spatial locations and surface initial temperature.**

Index Terms- **Jet Impingement, Wetting speed, Stagnation point, Surface quenching.**

I. INTRODUCTION

The jet impingement cooling technique is one of the commonly use quenching technique in industries viz. metal processing, manufacturing, electronics, automobile, nuclear, etc. due to its high heat removal capacity [7], [10], [14]. The quenching performance of a hot non ferrous and ferrous surface have been investigated under steady and transient state cooling condition several times [1] with water [1], [2] and other type of coolants [13]. The hot surface quenching performance is generally determined on the basis of rewetting parameters e.g. rewetting temperature [1]-[4], Wetting delay [11], maximum surface heat flux [9], [10] or the rewetting speed [2], [5], [6]. As the jet of coolant fluid strikes onto the hot surface, the formation of vapor bubbles restricts the direct contact of liquid with the hot surface. In fact these vapor bubbles retard the downstream progression of the coolant front over the hot surface.

Once the hot surface attain a certain temperature (referred as the rewetting temperature), at certain downstream spatial location, the progression of coolant font take place from that spatial location. The radial progression of the coolant front per unit time, in downstream direction is termed as rewetting speed. The rewetting speed is the measure of rapidity of surface cooling as desired in certain industries like metal processing, nuclear, respectively for controlling the material property and safety purpose under LOCA (Loss of Coolant Accident). The rewetting speed increases with the rise in coolant flow rate and jet diameter, however, reduces for the outward radial locations as compared to stagnation point region [1], [2], [5], [6]. In fact the rewetting speed is lower for non ferrous surface as compared to the ferrous surfaces as ferrous surfaces possess lower thermal diffusivity [9]

The surface quenching has been accessed several times earlier for rewetting temperature, wetting delay, maximum surface heat flux with coolant flow rate, coolant temperature, jet diameter, nozzle type, nozzle exit to test surface spacing surface type, surface size, surface orientation and initial surface temperature [1]-[6], [8], [9]. The determination of rewetting speed for ferrous surface has been reported for several coolant flow rate, coolant temperature and jet diameter [5], [6], [12]. It has been reported that it is the higher jet velocity and jet flow rate which is responsible to higher rewetting velocity not the higher jet diameter. The nozzle type and nozzle exit to surface spacing does not affect the rewetting velocity significantly [1], [3]. However, the effect of initial surface temperature with ferrous surface on rewetting speed has not been observed during jet impingement cooling of hot flat surface at downstream locations in particular. Therefore,

investigation has been carried out to study the movement of wetting front for radially outward spatial locations by varying the initial surface temperature.

II. EXPERIMENTAL INVESTIGATIONS

A. Materials

A hot flat surface of stainless steel (SS-304) was cooled with a downward impinging round water jet of 33 ℃ temperature and 3 mm diameter. The schematic of experimental setup is shown in Figure 2. Initially, water was stored in a reservoir (1) and supplied to the nozzle (6) with the help of a pump (2). The control valve (4) were used to regulate the water flow towards the nozzle through a rota-meter (3) and bypassed back to the reservoir. The hot surface temperate was recorded by an ungrounded 'K' type thermocouple (8) and a temperature indictor (9). The hot test surface position underneath to the nozzle can be adjusted by a handle (11). The nozzle (6) was fixed on a base that is further attached onto the two vertical supports of the experimental set up through nut and bolt arrangement, such that nozzle can be moved in vertical and horizontal direction. The various operating parameters used for the investigations are shown in Table (1).
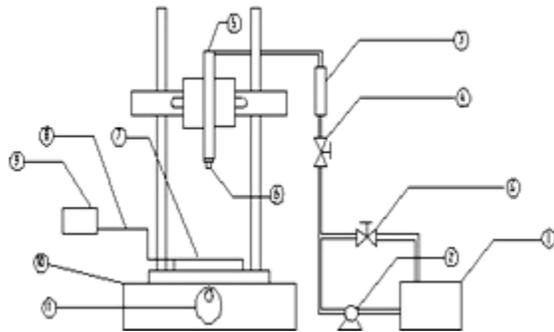
1. Reservoir 2. Water pump 3. Rota-meter 4. Control valve 5. Straight pipe 6. Nozzle 7. Test-surface 8. Thermocouple wire 9. Data-acquisition system 10. Base 11. Handle.

Fig. 2 Schematic of experimental set

B. Procedure

Initially, the test surface was heated up to desired initial temperature in a furnace and then kept on the experimental set up underneath the nozzle. The nozzle exit to test surface spacing, z, was maintained at 12 mm such that dimensionless nozzle exit to test surface spacing remained as z/d = 4. The quenching performance of the flat hot test surface was

determined by analyzing the wetting front progression towards the radial downstream locations, r. The videos of quenching process were captured with the rate of 30 fps and analyzed by using Dartfish video analysis software. The progression of wetting front up to a certain downstream location per unit time is considered as wetting speed, (u = r/t), in similar manner as reported earlier by Agrawal et al. 2013, 2016b [2], [5] and Akmal et al. 2008, [6]. The experiments were performed with different surface initial temperature by varying coolant flow rate as mentioned in Table 1. The experimental uncertainty for the wetting speed was found 10 % - 15 % for 10 mm spatial location and 2.5 % - 10 % for 40 mm spatial location. For every experiment a new test surface was used to avoid the effect of change in surface properties and oxidation due to previous experiments.

Table 1 Operating range of parameters

Experimental parameter	Operating range
Water flow rate, lpm	1.2, 5.1
Jet Reynolds number	11500, 48000
Water temperature, oC	33
Jet diameter, mm	3
Jet exit to surface spacing, mm	12
Surface length and width, mm	150x150
Thickness of test-surface, mm	2
Spatial locations, mm	10 , 40
Initial surface temperature, ℃	450 , 550, 620

III. RESULT ANALYSIS AND DISCUSSION

The impingement quenching experiments were performed on the hot flat surface at 450 – 620 ℃ initial temperature of 2 mm thickness. During experiments it was observed that the hot surface at the stagnation point get cooled immediately as the jet strikes to the surface. However, with the progression of wetting front towards the downstream spatial location, some amount of coolant fluid splashes obliquely away from the hot surface in the upward direction, as shown in Fig. 3.

It is observed that the violent boiling of fluid takes place at the periphery of the wetting front, possibly this is the region of transition boiling. Since, initial

temperature of test surface is of the order of 620 - 450 ℃, thus, the temperature of coolant at the edge of wetting front may reach to the superheated stage. With the progression of wetting front the high temperature coolant further absorbed the heat from the hot surface and leads to formation of vapor bubble. The frequent bubble formation and subsequent collapse may be the possible reason for this splashing phenomenon of the coolant from the hot test surface. With the expense of time the intensity of splashing phenomena reduces particularly for the downstream spatial locations, perhaps due to reduction in surface temperature from its initial temperature.

The wetting speed for the investigated initial surface temperature at 10 mm and 40 mm locations with water flow rate of 1.2 lpm and 5.1 lpm is shown in Fig. 4.

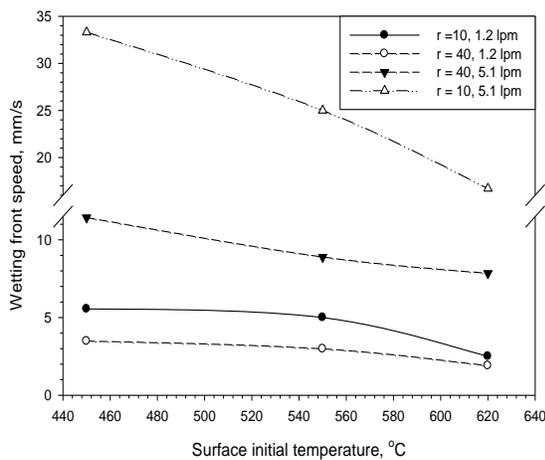Fig. 3 Image of coolant flow over hot surface

Fig. 4 Effect of initial surface temperature and jet flow rate on wetting speed.

From Fig. 4 it has been observed that for a certain flow rate and spatial location the wetting speed reduces with the increase in surface initial temperature. The reduction in wetting speed exaggerated for the higher order of surface initial temperature. The wetting speed reduces in the range of 10 - 14 % with the water flow of 1.2 lpm and in the range of 20 - 25 percent with 1.5 lpm, for the investigated spatial locations by increasing initial surface temperature from 450 ℃ to 550 ℃. Whereas, with further rise in temperature up to 620 ℃, the reduction in wetting speed is observed in the range of 50 -55 % at 10 mm location and 35 – 45 %   at 40 mm location for the investigated water flow rate. With the rise in surface initial temperature, the associated stored energy increase. Thus, lager amount of heat has to be absorbed for a certain coolant flow rate and hence the wetting speed reduces. The reduction in the wetting speed is larger for the 10 mm location as compared to the 40 mm location with the increase in surface initial temperature. The tendency of coolant splashing may possible reason for this observation. The greater amount of coolant splash out away from the surface with the surface of higher initial temperature. The higher surface temperature lead to enhanced frequency of bubble formation and collapsing, resulting greater amount of coolant splashing, away from the surface. Therefore, with reduces initial amount of coolant the reduction in the wetting speed for 10 mm location is higher as compared to the 40 mm spatial location.

In is also observed that the wetting speed reduces for the downstream spatial locations. The rise in spent out fluid enthalpy, flow retardation for downward direction, larger peripheral surface area to be cooled with the available coolant and increase in thermal / hydraulic boundary layer thickness for downstream locations may be the possible reason for this. The spatial reduction in the wetting speed is higher for lower temperature surfaces as compared to the higher temperature, which is further higher with higher coolant flow rate. This result reflects that with the rise in coolant flow rate, the surface near the impingement point get cooled much earlier as compared to the farthest downstream location. However with the rise in surface temperature, the initial splashing of fluid hampers the quenching performance of surface even for the location near to the impingement point.

IV. CONCLUSIONS

The quenching performance increase with the rise in coolant flow rate however, reduces with the rise in surface initial temperature and for the downstream spatial location.

For a certain spatial location the reduction in the wetting front is larger for the extreme temperature surfaces due to possible increase in stored energy.

The spatial reduction in the wetting front is larger for the surface of lower initial temperature as compared to the higher temperature surfaces due to comparatively higher amount of jet fluid splashing as the jet strikes to the hot surface.

This experimental investigation incorporated some of the parameters associated with the jet impingement hot surface quenching, however an exhaustive research can also be performed by incorporating other operating parameters. The results can be presented in the form of generalized correlation that may be helpful to the researchers and industrialist particularly for controlling specific metal properties during casting and extrusion processes.

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