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Effect of surface thickness on the wetting front velocity during jet impingement surface cooling

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Abstract A hot stainless steel (SS-304) surface of 450 ± 10 °C initial temperature is cooled with a normally impinging round water jet. The experiments have been performed for the surface of different thickness e.g. 1, 2, 3 mm and jet Reynolds number in the range of $Re = 26{,}500$–$48{,}000$. The cooling performance of the hot test surface is evaluated on the basis of wetting front velocity. The wetting front velocity is determined for 10–40 mm downstream spatial locations away from the stagnation point. It has been observed that the wetting front velocity increase with the rise in jet flow rate, however, diminishes towards the downstream spatial location and with the rise in surface thickness. The proposed correlation for the dimensionless wetting front velocity predicts the experimental data well within the error band of ±30 %, whereas, 75 % of experimental data lies within the range of ±20 %.

List of symbols

Br	Brun number $\left(\frac{k_j}{k_s}\right)\left(\frac{w}{l}\right)Re^{\frac{1}{2}}Pr^{\frac{1}{3}}$
c_p	Specific heat of material (kJ/kg K)
d	Jet diameter (m)
k	Thermal conductivity (W/m K)
l	Length of test surface (m)
Pe	Peclet number, dimensionless wetting front velocity, uw/α_s
Pr	Prandtl number, υ/α_j
Q	Water flow rate (lpm)
r	Distance away from stagnation point in radial direction (m)
Re	Reynolds number, Ud/υ
t	Time (s)
t_d	Wetting delay (s)
T	Temperature (°C)
u	Wetting front velocity (m/s)
U	Jet velocity at nozzle exit (m/s)
w	Thickness of test surface (m)
z	Spacing between jet exit to test surface (m)
z/d	Dimensionless nozzle exit to test surface spacing

Greek symbols

υ	Kinematic viscosity of water (m^2/s)
α	Thermal diffusivity of surface (m^2/s)
ρ	Density of material (kg/m^3)

Suffix

j	Jet
i	Initial
s	Test-surface

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1 Introduction

The jet impingement surface quenching is being extensively used in several industrial applications due to its capability of high heat removal rate, even from the smaller surface [1, 2]. The jet impingement cooling method is predominantly applied in several industries viz. the metal, electronic, nuclear, automobile etc. [2–4]. The investigations for the jet impingement surface quenching with different operating parameters have been reported several times under the steady and transient cooling condition [5–7]. These operating parameters includes coolant type and temperature [4, 8, 9], nozzle configuration and jet diameter [6, 10, 11], hot surface

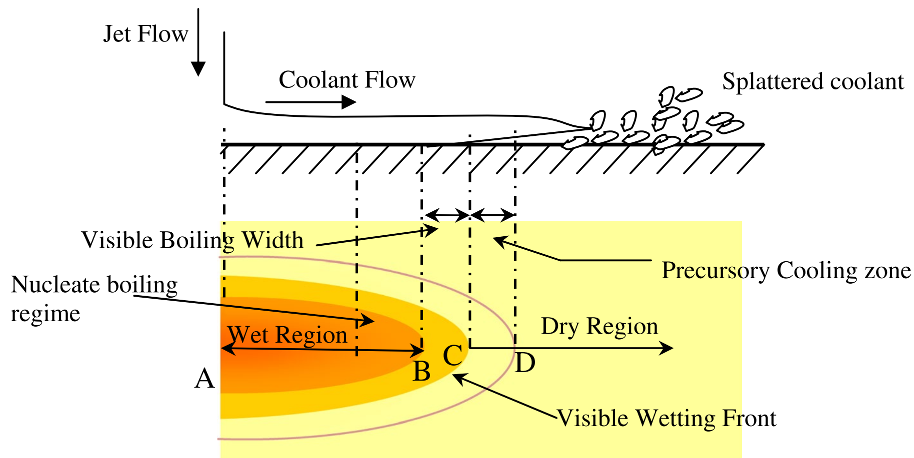

Fig. 1 Coolant flow and boiling regimes over hot surface

configuration, orientation and initial surface temperature [1–4, 7] etc.

The jet impingement surface quenching under transient condition involves a complex thermal hydrodynamics of fluid. Thus, this cooling process needs to be addressed thoroughly, particularly when the high and rapid heat removal rate is desired. With the impingement of water jet on the hot surface, a layer of vapour bubbles is formed over the surface of sufficiently high temperature. Thus, the impinging coolant is not able to wet the hot surface immediately as it strikes to the surface. The blanket of vapour bubbles over the surface prevents the direct contact of coolant with the hot surface. The continuous supply of fresh coolant destroys the vapour layer at the stagnation point and results in wetting of hot surface [8, 12]. With the elapse of cooling time, as the surface temperature drops, the wetting front progresses towards the downstream locations.

During quenching, at certain moment the hot surface witnesses all the four mode of boiling heat transfer simultaneously at different radial locations as shown in Fig. 1 [4, 13]. When a jet of sub-cooled coolant strikes on to the hot surface, eventually, a dark cooling zone is formed at the stagnation point. With time, this dark zone spread radially away from the stagnation point over the hot surface. The dark cooling zone comprises of two zone i.e. inner wet zone and outer boiling zone as marked by ‘AB’ and ‘BC’ respectively in the Fig. 1. The temperature at the middle of wet zone is the least and termed as the regime of forced convection heat transfer, whereas, outer wet zone corresponds to the nucleate boiling regime. The boiling zone, ‘BC’ termed as the transition-boiling regime and its width depends on the surface properties [13]. This region also exhibits the highest drop in surface temperature during the quenching. The visible leading edge ‘C’ of this cooling zone is termed as the wetting front and at the edge of this zone i.e. at point ‘C’, the wetting front detach from the hot surface due to abrupt formation of vapour bubbles. Beyond the cooling zone, ‘BC’, the hot surface is dry and termed as ‘precursory cooling zone’ (PCZ). This precursory cooling zone is marked as ‘CD’ in the Fig. 1. The coolant has not yet covered this region but the heat is conducted from this precursory cooling zone (PCZ) to the inner cooling zone of the solid surface [14]. Beyond ‘PCZ’ the outer region remains unaffected by the quenching phenomena and the main mode of heat transfer to the surrounding is convection/radiation.

The performance of surface quenching under transient condition is evaluated generally on the basis of surface heat flux or by the advancement of wetting front on the hot surface [2–4, 14–17]. The linear advancement of wetting front towards downstream locations per unit time is termed as the wetting front velocity [3, 15]. The wetting front velocity is normally evaluated by determining the time taken to travel certain known distance or the distance between two marked locations by the wetting front [6, 17, 18]. The wetting front velocity increases with the increase of liquid subcooling, pressure, flow rate, jet velocity and the jet diameter [2–4, 17–20]. However, decreases with the rise in initial surface temperature and input heat [2, 14, 21, 22]. It has been reported that the effect of jet flow rate on the wetting front velocity is more for the surface of lower initial temperature than for the surface of higher initial temperature. The wetting front velocity for horizontal tubes is found nearly 20–30 % lower as compared to with vertical tubes [21]. The surface roughness increases the wetting front velocity due to increase in rate of heat transfer [23]. Mitsutake and Monde [22], reported that on the hot copper surface wetting front movement is slower as compared to the steel surface, due to higher thermal inertia of copper, $(\rho c_p k)^{1/2}$. Xu and Gadala [24] also reported that the wetting front velocity is higher for SS-316 surface as compared to the DQSK steel surface. This finding is in agreement to the Mitusutake and Monde [22] results, as the SS-316 surface has higherthermal conductivity as compared to the DQSK steel [22, 24]. Since,

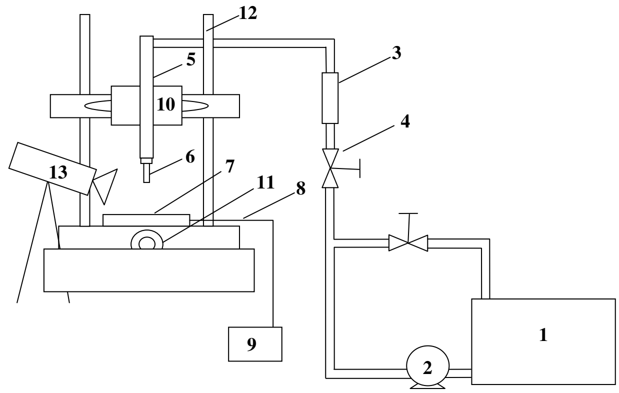

Fig. 2 Schematic of experimental set up. *1* Reservoir, *2* water pump, *3* rota-meter, *4* control valve, *5* straight pipe, *6* nozzle, *7* test-surface, *8* thermocouple wire, *9* data-acquisition system, *10* base, *11* lateral movement handle, *12* vertical support, *13* digital camera

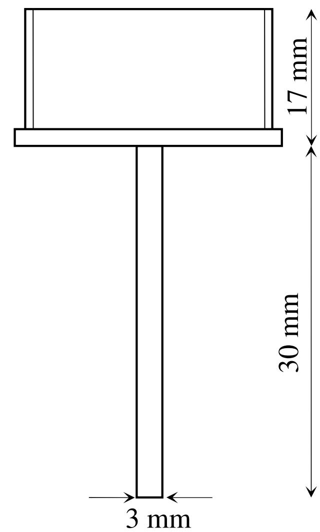

Fig. 3 Schematic of nozzle

in literature the effect of surface thickness on the progression of wetting front velocity has not been observed particularly with hot stainless steel surface (SS-304). Therefore, an experimental investigation has been carried out and a correlation is proposed to determine the dimensionless wetting front velocity for the experimental range of parameters.

2 Experimental set up and procedure

A hot stainless steel surface was cooled with a round water jet of 3 mm diameter and 33 °C temperature. The schematic of experimental setup is shown in Fig. 2. Water as coolant was stored in a reservoir (1) and supplied to the nozzle (6) by using a pump (2). The control valve (4) was used to regulate the flow towards the nozzle through a rota-meter (3). The hot test surface (7) was placed underneath to the nozzle (6) attached to a long pipe (5). The test surface temperature was observed by a 'K' type ungrounded thermocouple (8) and a temperature indictor (9). The position of the test surface underneath to the nozzle can be adjusted by using a hand operated handle (11). The nozzle (6) is attached to a long straight pipe (5) that was supported on a base (10). This base is attached on two vertical supports (12) of the test section through nut and bolt arrangement, such that nozzle can be adjusted in horizontal and vertical direction. A digital camera (13) was placed in front of the test section to capture the quenching process. The schematic of nozzle used for the study is shown in Fig. 3 and the operating parameters used for the investigations are shown in Table 1.

Initially, the test surface of a certain thickness was heated up to 500 °C temperature in a furnace and then this hot test surface was kept on the set up, below the nozzle assembly. The nozzle exit to test surface spacing for the entire investigations was maintained at 12 mm such that

Table 1 Operating range of experimental parameters

Experimental parameter	Operating range
Water flow rate (lpm)	2.2–5.1
Jet Reynolds number	26,500–48,000
Nozzle exit jet velocity (m/s)	6.6–12.0
Water temperature (°C)	33
Jet diameter (mm)	3
Jet exit to surface spacing (mm)	12
Test surface length and width (mm)	150 × 150
Thickness of test-surface (mm)	1, 2, 3
Spatial locations (mm)	10, 20, 30, 40
Initial surface temperature	450 ± 10 °C

dimensionless nozzle exit to test surface spacing remained at $z/d = 4$. The jet impinging quenching process was initiated once the test surface attained the desired initial temperature i.e. 450 ± 10 °C. The quenching performance of the hot test surface was evaluated by analysing the downstream progression of wetting front over the hot surface. The video of quenching process was captured with the rate of 30 fps using Nikon D3100 digital camera. These captured videos were further analysed with Dartfish video analysis software and the time taken, t, to reach the wetting front at a certain downstream location, r, was determined. With the known value of time, for a certain radial location, the wetting front velocity, ($u = r/t$), was evaluated in similar manner as reported earlier by other investigators [6, 17, 18]. The experiments were performed with different surface thickness and coolant flow rate as mentioned in Table 1. The experimental uncertainty for the wetting front velocity was determined using the method suggested by Kline and McClintok [25]. The maximum uncertainty of the wetting front velocity was found in the range of 10–25 % for 10 mm spatial location and minimum uncertainty for 40 mm spatial location in the range of 2.5–3 %. For each set of experiment, a new test surface was used for the investigation to avoid the effect of surface oxidation and change in surface properties due to previous experiments.

3 Results and discussion

The jet impingement cooling experiments were performed on the hot test surface of three different thickness e.g. 1, 2, 3 mm having 450 ± 10 °C initial temperature. During experiments it is observed that initially jet strikes at the impinging point i.e. at the stagnation point, onto the hot test surface and immediately a wet patch is formed at the stagnation point Fig. 4d. However, with the progression of wetting front towards the downstream spatial location, some amount of impinging fluid splashes obliquely in the upward direction, away from the hot surface, as shown in Fig. 4e–h. Somewhat, the phenomenon of wet patch formation and coolant splashing have also been reported by many other investigators with Gold, Inconel, Copper, Brass and Steel surfaces, maintained at different initial temperature [22, 26, 27]. A wet patch of around 3–5 mm is formed beneath to the nozzle immediately with the impingement of jet. However, beyond the periphery of the wetting front the surface remains dry. The violent boiling takes place at the periphery of the wetting front, possibly this is the region of transition boiling as explained earlier in Fig. 1. Since, initial temperature of test surface is of the order of 450 °C, thus, the temperature of spent out coolant at the wetting front edge will approach to the saturation temperature of coolant. Therefore, the higher temperature coolant absorbed the heat from the surface and lead to possible formation of vapour bubble. The frequent bubble formation and subsequent collapsing may be the possible reason for this splashing phenomenon of the coolant from the hot test surface. With the elapse of cooling time the intensity of splashing

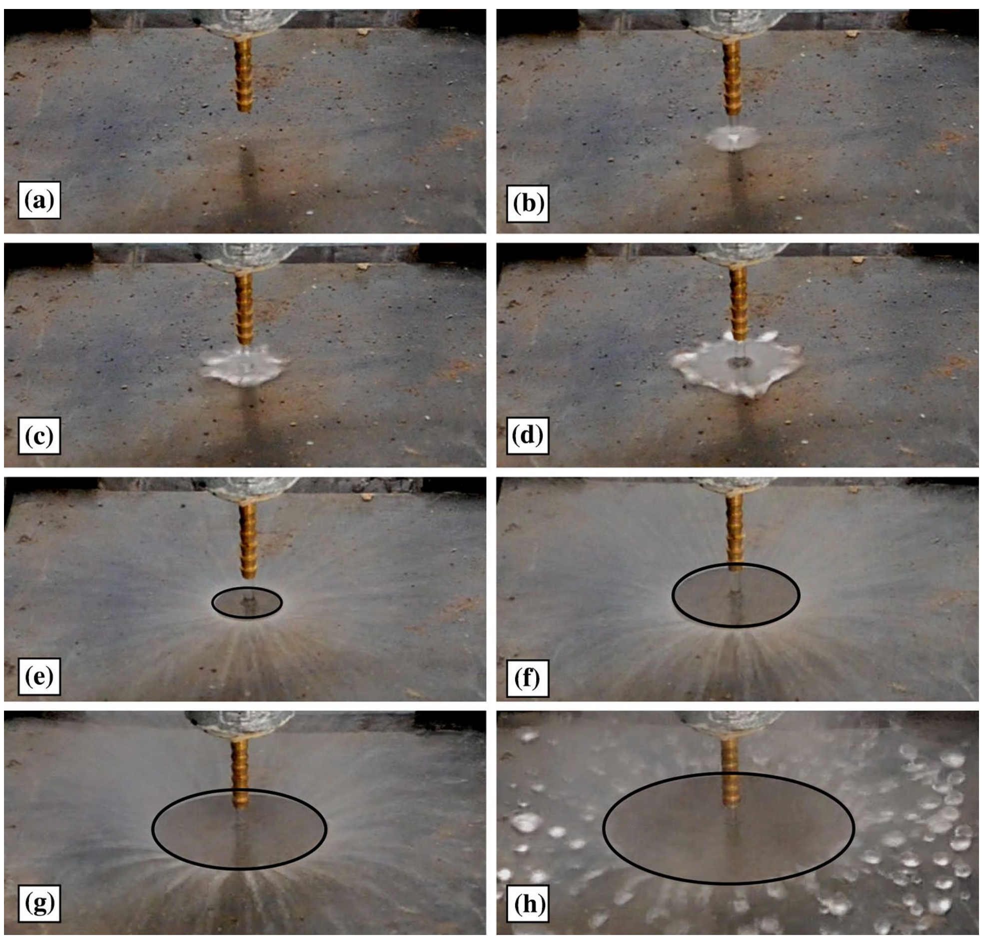

Fig. 4 Images of coolant flow over the hot surface, **a** before the jet impingement, **b–d** jet strikes to the hot surface, **e** wetting front at 10 mm, **f** wetting front at 20 mm, **g** wetting front at 30 mm, **h** wetting front at 40 mm

reduces, may be due to reduction of surface temperature from its initial temperature of 450 °C particularly for the downstream spatial locations (Fig. 4h).

The spatial variation of the wetting front velocity with test surface of different thickness is shown in Fig. 5a, b, respectively for the jet Reynolds number of $Re = 26{,}500$ and 48,000. It has been observed that at a certain coolant flow rate, with the increase in surface thickness, the wetting front velocity reduces. Since, the test surface is heated up to initial temperature of 450 °C before the experiments. Therefore, with the surface of larger thickness e.g. 3 mm the initial stored energy is higher as compared to the surface of 1 mm thickness. For a certain coolant flow rate and coolant temperature, the amount of energy available to be removed with thicker surface is larger as compared to the energy available with thinner surface. Several investigators have analytically evaluated the process of jet impingement surface quenching by considering the effect of conjugate heat transfer under transient and steady state condition [28–30]. The heat transfer characteristics of convective boundary layer flow over a flat plate are very much affected by the type of the thermal boundary conditions imposed at the top of the surface, which, is in contact with the fluid. Mossad [28] recommended that the effect of conjugate heat transfer should not ignored if the Brun number ($Br > 0.15$), otherwise it may leads to an error of 5–10 % in the evaluated heat transfer performance. The Brun number for the present experimental investigation during rewetting state is estimated as $Br < 0.15$, thus the effect of conjugate heat transfer can be ignored. Nevertheless, even if the conjugate heat transfer is taken into account, there is some temperature gradient that exist between bottom and the top of the hot surface. The amount of temperature gradient will be larger for thick surface as compared to the thin surface [29]. Hence, the quenching of thin surface is much faster than the thick surface or the surface of 1 mm thickness attains the rewetting state much earlier than the surface of 3 mm thickness. Due to above mentioned facts, after the jet impingement, with thicker surface, the rise in enthalpy of coolant or the coolant temperature will be more as compared to the thinner surface. With larger coolant temperature heat absorbing capacity reduces and the thickness of thermal boundary layer increases, perhaps this may further enhances the formation of vapour bubbles for the downstream locations between coolant and hot surface. All these effect cumulatively hinder the heat transfer and consequently progression of wetting front for the downstream locations, away from the stagnation point. Therefore, the wetting front velocity for the thicker surface e.g. 3 mm is found lower than the wetting front velocity obtained with other two investigated surface thickness e.g. 2 and 1 mm. Hall et al. [7] and Fillipovic et al. [19] have also mentioned in their experimental study that the rise in stored energy is

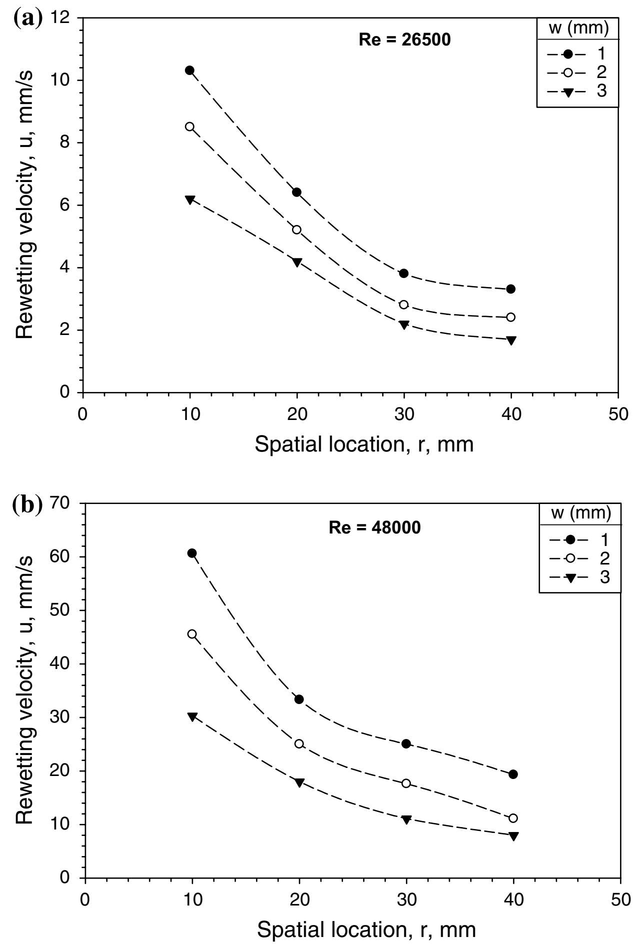

Fig. 5 Effect of surface thickness on wetting front velocity

responsible for the reduction in wetting front progression. Moreover, Rahman and Hernandez [30] have also reported that during jet impingement surface cooling, the thicker surface takes longer time to attain the steady state condition. This observation is also in line with our results that at certain spatial location the time taken to attain the wetting state by the thicker surface is delayed as compared to the thinner surface. This results in lower wetting front velocity for thick surface, as the wetting front velocity, at certain spatial location is inversely proportional to the time taken to attain the wetting state or the wetting delay ($u = r/t_d$) [6, 15].

The percentage reduction in wetting front velocity for thicker surface is enhanced further with the rise in coolant flow rate. The wetting front velocity reduces approximately by 30 % with 3 mm thickness surface as compared with the surface of 1 mm thickness at $Re = 26{,}500$. Whereas, the corresponding reduction for the entire spatial locations with 3 mm thickness surface is observed approximately 60 % as compared to 1 mm thickness, at $Re = 48{,}000$. As discussed earlier, this observation can also be attributed by

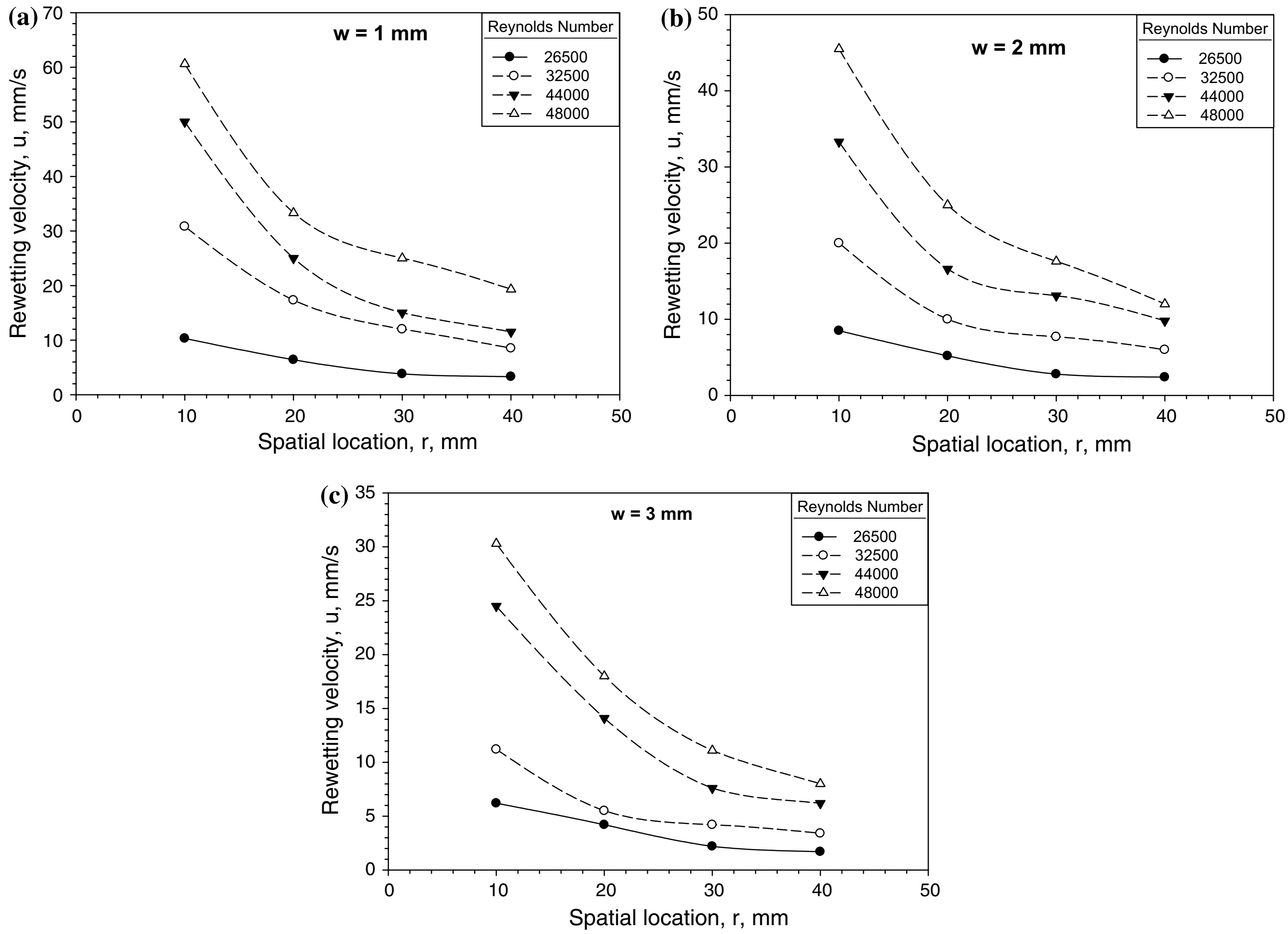

Fig. 6 Effect of coolant flow rate on wetting front velocity

the splashing of coolant, away from the hot surface. Possibly, with the rise in coolant flow rate more amount of fluid is available for splash out, away from the test surface, without participating in the quenching process. However, the wetting front velocity increases with the rise in coolant flow rate irrespective of change in surface thickness, as shown in Fig. 6. With the rise in coolant flow rate or the jet Reynolds number from $Re = 26{,}500$ to 48,000, the wetting front velocity rises approximately 5 times for 1 mm thickness surface. Whereas, the corresponding rise in wetting front velocity for 3 mm thickness surface is approximately 4 times for the entire spatial locations. The lesser rise in the wetting front velocity with the rise in jet flow rate for 3 mm thick surface as compared to surface of 1 mm thickness, can be attributed same as mentioned above. The rise in wetting front velocity with the increase in jet Reynolds number may be attributed by the enhancement of the turbulence in jet, which leads to an increase in convective heat transfer. This is believed that the effect of jet momentum enhances the breaking of established vapour layer on the hot surface that results in enhanced cooling or increase in wetting front velocity.

It has also been observed in Figs. 5 and 6 that irrespective of change in flow rate or surface thickness the wetting front velocity reduces for the downstream spatial locations. The wetting front velocity reduces approximately by 70 % from the 10 mm spatial location to 40 mm location for the entire investigated range of jet flow and surface thickness. The reduction of wetting front velocity for downstream locations can be attributed by several factors e.g. rise in spent out fluid enthalpy, flow retardation, larger peripheral surface area to be cooled with the available jet flow rate and rise in thermal/hydraulic boundary layer thickness for downstream locations [6, 17, 22].

A correlation for the dimensionless wetting front velocity has also been proposed based on the experimental results for the investigated range of operating parameters. The proposed correlation is valid for the range of parameters i.e. $26{,}500 \leq Re \leq 48{,}000$, $1 \leq w \leq 3$, $10 \leq r \leq 40$ and $z/d = 4$ with Stainless Steel (SS-304) surface of 450 °C initial temperature. The proposed correlation predicts the dimensionless wetting front velocity within an error band

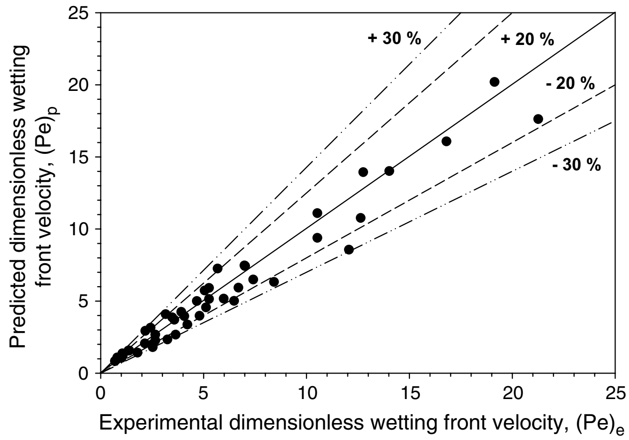

Fig. 7 Comparison of experimental dimensionless wetting front velocity with those predicted by proposed correlation

of ±30 %, in which 75 % data lies within an error band of ±20 % (Fig. 7).

$$Pe = \frac{uw}{\alpha_s} = 3.1 \times 10^{-11} Re^{2.62} Pr^{-4.93} \left(\frac{r}{d}\right)^{-0.91} \times \left(\frac{w}{d}\right)^{0.33} \left(\frac{k_j}{k_s}\right)^{2}$$

Since, no generalised correlation for the wetting front velocity is available in literature, particularly for the investigated range of experimental parameters, thus, the proposed correlation cannot be compared directly with others results. However, the present experimental results are in line with the observations reported by other investigators for various operating parameters. Within 10–40 mm downstream spatial locations, experimental wetting front velocity is found in the range of 1.7–30.5 mm/s for 3 mm surface thickness and in the range of 3.3–60.6 mm/s for 1 mm surface thickness. Agrawal et al. [31] with an Infrared camera, for SS-316 surface of 800 °C initial temperature and 3 mm thickness, with jet of 2.5 mm diameter and Re = 5000 at 10 mm spatial location has also reported the wetting front velocity as 3.1 mm/s. In another work Akmal et al. [2] for horizontal cylindrical steel surface of 7.82 mm thickness at 500 °C initial temperature found the wetting front velocity as 28.9 and 2.5 mm/s respectively at 19 and 26 mm downstream locations with the jet of 3 mm diameter and jet velocity of 5.0 m/s.

Moreover, based on experimental results, Hatta et al. [32] correlated the wetting radius merely in term of time, without considering any other operating parameter. Therefore, these relations cannot be used for comparing the present experimental results. In another investigation Mozumder et al. [4] with jet of 2 mm diameter, 50 °C temperature and 5 m/s velocity, on the horizontal flat steel surface of 59 mm thickness at 600 °C initial temperature, for 20 and 40 mm spatial locations, reported the wetting front progression respectively as 2 and 0.6 mm/s. These results are lower than our reported results, since, the Mozumder et al. [4] experiments are for thicker and higher initial surface temperature with jet of lower degree of sub-cooling. Since, it has already has been established in literature that the wetting front velocity reduces with the rise in coolant and surface initial temperature [14, 22, 24]. In fact, the reduction in the wetting front progression for thicker surface is also in line with our investigation for different surface thickness. Similarly Karwa et al. [20] have reported the wetting front propagation as 1 and 3 mm/s at 24 mm downstream location respectively with jet velocity of 2.85 and 6.4 m/s, for a horizontal flat steel surface of 20 mm thickness at 900 °C initial temperature. Whereas, we have found the wetting front velocity at 20 mm spatial location as 4.2 mm/s with surface of 3 mm thickness for jet velocity of 6.6 m/s or Re = 26,500. The result of Karwa et al. [20] for same spatial location is lower as compared to our results, since, their study is for the surface of higher initial temperature and higher thickness. Hatta et al. [32] with jet of 10 mm diameter and flow rate of 2.21 lpm on 10 mm thickness steel surface of 900 °C initial temperature at 20 and 40 mm spatial locations found the wetting front velocity respectively as 6.75 and 3.37 mm/s. With the increase in flow rate to 6.75 lpm, the wetting front velocity for respective locations rises to 13.6 and 6.8 mm/s [32]. The spatial variation of wetting front velocity and effect of coolant flow rate as reported by Hatta et al. are in line with our reported experimental result. Even the result with 2.21 lpm are almost coinciding with our experimental results for the surface of 1 mm thickness with Re = 26,500 (2.8 lpm) at 20 and 40 mm spatial location. Apparently, with the surface of lower initial temperature, (Ti = 450 °C) and lower surface thickness, (w = 1 mm) our reported wetting front velocity should be higher than Hatta et al. [32] results. However, these observations can be explained by considering the nozzle exit to test surface spacing and nozzle exit jet velocity or jet Reynolds number. Hatta et al. [32] results are for dimensionless nozzle exit to test surface spacing, z/d = 20, and nozzle exit jet velocity, V_j = 0.47 m/s or Re = 6200, whereas, our observation are for z/d = 4, and V_j = 6.6 m/s or Re = 26,500. Perhaps with the jet of high velocity or higher jet Reynolds number, at lower jet exit to surface spacing more amount of coolant splashes away from the hot test surface without participating in the quenching process. Hence, results for wetting font velocity are lower than expected, when compared with Hatta et al. observations. Some of the experimental results published by various investigators are depicted in Fig. 8 along with our experimental results with Re = 26,500, w = 1–3 mm for different spatial locations.

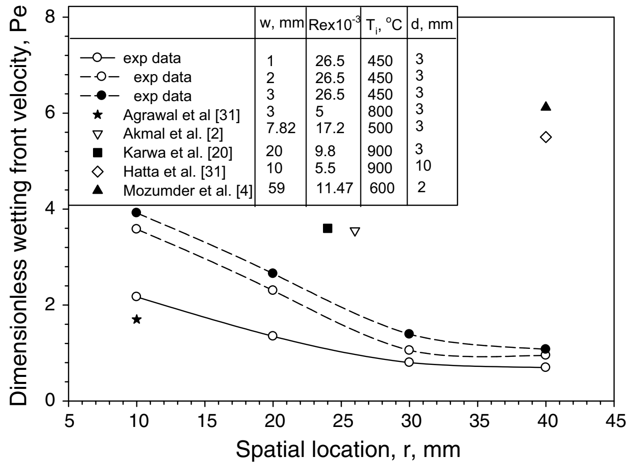

Fig. 8 Comparison of experimental data with published results of other investigators

With the review of available literature, it has been observed that our experimental results for the wetting front progression are well within the range of published results with the horizontal surfaces of different thickness and configuration. Moreover, no generalized correlation is available for the wetting front velocity, obtained with different operating parameters. Therefore, no direct comparison can be made for the wetting front progression with the available results.

4 Conclusions

The following conclusions can be drawn from this experimental investigation for the jet impingement surface cooling of varying thickness:

1. It has been observed that with the impingement of jet on the hot surface, the region of stagnation point cooled immediately, followed by the progression of wetting front towards the downstream spatial locations. The coolant available at the periphery of wetting front splashes out obliquely in upward direction, away from the hot surface. The intensity of coolant splashing reduces for the extreme downstream location with the expense of time.
2. For a certain coolant flow rate and spatial location, the wetting front velocity on the hot surface reduces for the thicker surface. The reduction in the wetting front velocity for the thicker surface is further enhanced with the rise in coolant flow rate. This may be attributed by the larger splashing of coolant away from the hot surface, at the periphery of the wetting front, particularly for higher coolant flow rate.
3. For a certain surface thickness, the wetting front velocity reduces towards the downstream spatial locations, however, increases with the rise in coolant flow rate for the entire range of downstream spatial locations examined.
4. The following correlation proposed for dimensionless wetting front velocity predicts the experimental results in the error band of ±30 %, in which 75 % experimental data lies within the error band of ±20 %. This correlation is valid for the range of parameters i.e. 26,500 $\leq Re \leq$ 48,000, $1 \leq w \leq 3$, $10 \leq r \leq 40$ and $z/d = 4$ with Stainless Steel (SS-304) surface of 450 °C initial temperature.

$$Pe = \frac{uw}{\alpha_s} = 3.1 \times 10^{-11} Re^{2.62} Pr^{-4.93} \left(\frac{r}{d}\right)^{-0.91} \times \left(\frac{w}{d}\right)^{0.33} \left(\frac{k_j}{k_s}\right)^{2}$$

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