Experimental Investigation of the Water Jet Cooling of a Hot Steel Plate

Hormando Leocadio
Research & Development Center, Usiminas Steel, Ipatinga, 35160-900, Brazil
hormando.leocadio@usiminas.com

***Abstract* — Impinging water jets are widely used as a fast cooling system in metal industry due their high heat removal rate. The microstructure and mechanical properties of a hot strip mill depend on the temperature control on runout table, what makes critical the knowledge of heat transfer behavior in jet impingement cooling systems. This paper presents an experimental and numerical study of the heat transfer during of the heat transfer behavior of a hot steel plate cooled by an impinging circular water jet. The thermal characteristics were examined by the inverse heat conduction method that gave the heat fluxes and temperatures on top surface from measured temperatures into the plate. Temperature and water flow of the jet have a significant effect on the heat removal capacity in jet impingement zone. The surface heat flux increases with the reduction of jet temperatures. Higher water flow rate of the jet cause an increasing on cooling rate. Results will contribute for enhancement of effective fast cooling systems.**

Keywords— Hot steel rolling mill; Jet impingement cooling; Heat transfer; Fast cooling system.

I. Introduction

Many industrial applications use free impinging jets, because of the high heat removal rates obtained by relatively simple equipment [1]. Jet impingement boiling is used in many industrial applications involving rapid cooling, temperature control in emergency core cooling of nuclear power plants, and power dissipation in the micro-electro-mechanical systems devices [2]. Metal industries widely employ water jet as a means of precisely controlling temperature during cooling process of hot rolling, continuous casting, extrusions, forging and hot strip mill cooling on run-out tables [3, 4, 5]. Cooling control is one of the most critical processes to ensure required mechanical properties and grain structure in a steel strip mill on the runout table [3, 6, 7, 8]. For strip travelling up to 20 m/s on runout table, the finishing and the coiling temperatures are around 900°C and 150-750°C, respectively. The steel strip is cooled simultaneously on top and bottom surfaces by the several arrays of round impinging water jets [8]. Whence, the importance to get the accurate heat transfer coefficient in order to design efficient cooling control systems [7, 9, 10, 11]. The heat transfer includes internal conduction, forced and boiling convection, air convection, radiation and heat generation from material phase transformation. Water jet impingement zone counts for more than 90% of the heat removed [6]. The entire heat transfer process still is not fully understood because the heat transfer mechanism involves a complex mixed phenomenon of water impingement (film boiling, wetting, nucleate and transition boiling) on a moving surface [4, 6, 7, 8, 10]. According to literature [12, 13, 14], elevated heat fluxes with high cooling rates in jet impingement on hot steel surface start only after the hot surface become wetted (establishing of the liquid-solid contact). Other experimental jet quenching studies [15, 14] reported the sudden appearance of a dark circle under the jet as the visible proof of this wetting phenomenon. Within this jet impingement dark (wetted) zone an effective cooling occurs, attributed to the high subcooling and impinging velocity of the jet, which prevent development of inefficient film boiling [8].

Authors disagree on the heat transfer regime in impinging zone during the cooling of the hot strip steel. Ochi et al. [16] and Ishigai et al. [17] showed that subcooling of water strongly affects the heat flux and prevents the formation of the film boiling (vapor layer) in the jet impingement zone. Some authors [7, 6, 10, 18, 19] suggested that, under impinging jet on a moving hot strip, the single-phase (without boiling activity) regime occurs and should be used in cooling models. Contrary, Timm et al. [20] argued that boiling activity regime have to occur due to high heat flux and surface temperature and the vapor bubbles formed on the hot surface condenses into subcooled liquid. Karwa & Stephan [12] reported wetted surface at 650°C without bubble boiling activity, for T_j = 25°C and the surface heat flux (q_s) above 6 MW/m². Lee et al. [14] also reported the absence of bubbly activity within the wetted zone for a 900°C-plate cooled by 20°C-jet. Further, results published [8, 21, 14] show discrepancies among heat transfer coefficient (HTC) values. Filipovic et al. [8] developed a mathematical model to predict the thermal behavior of steel strips cooled by array of round jets. They [8] considered effective heat removal occurs in wetted circle (dark circle) under jet impingement and depends on surface temperature (T_s), jet velocity (V_j) and jet temperature (T_j). Cox et al. [6] considered a single-phase regime within impingent zone and a constant HTC, in their strip cooling model. The present the study intends contributing to the understanding of the heat transfer modes during jet cooling of hot steel rolling mill to development of the efficient cooling control systems.

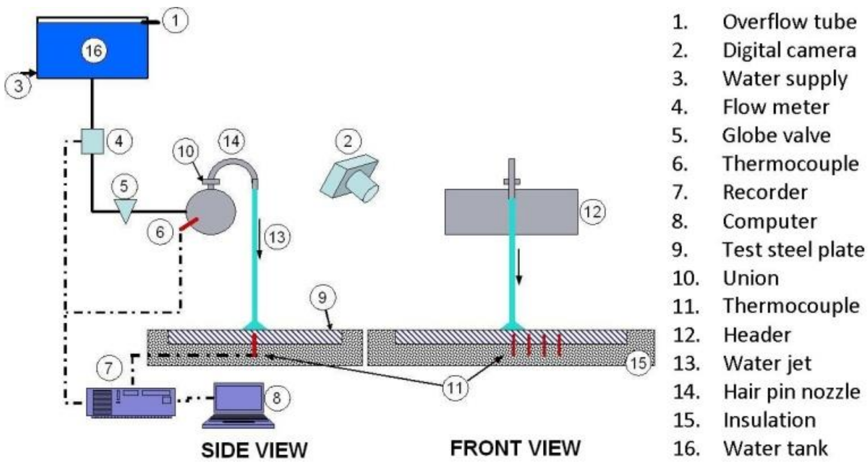

Fig. 1. *Outline of the experimental for the jet cooling of hot steel plate.*

An experimental apparatus was constructed at the Research & Development Center of USIMINAS Steel to study the heat transfer behavior during the cooling of a steel plate heated to 743°C by an impinging circular water jet at 12°C and 27°C with flow rate of 3 and 6 ℓ/min. The effects of those parameters were analyzed by a two-dimensional axisymmetric finite element model based on the transient inverse heat conduction method that predicted the heat flux and temperature on the top surface from temperature histories measured in the test plate.

II. Experimental Apparatus and Methods

Fig.1 shows outline of the experimental facilities: the coolant was ordinary city water stored in a tank (16), with equivalent pressure is 70 kPa, creating a water jet flow (13) at the exit (14) of a U-tube (radius of curvature 70 mm), with an inner diameter of 10 mm. U shaped tube (14) keeps the water a stable flow state, without the presence of air and compatible with ones used the cooling system of the steel industry. The overflow tube (1) keeps the water level in the tank (16) constant, thus assuring a constant pressure in the U-tube. The test plate (9) was heated to the test temperature in an electrical furnace of 75 kW, 800 mm wide, 1000 mm long and 600 mm tall, capable of heating up to 1300°C. The test plate material was stainless steel type 304 that avoids surface oxidation and the heat generation, caused by phase transformation, which occurs with carbon steels.

A square plate of 150 x 150 x 14 mm³ was used. On the plate sides without water impingement, insulation material was used with a thermal conductivity of 0.170 W/m°C (at 1090°C) and 50 mm thickness. The data acquisition system, composed of 10 channels, allowed for an acquisition rate of 20 Hz. Results of an uncertainty analysis of the primary measurements of radial position (r), time (t), axial coordinate (y), temperature (T_m), water jet temperature (T_j), and water jet velocity at nozzle exit (V_j) are ± 0.05 mm, ± 0.01 s, ± 0.05 mm, ± 0.3 %, ± 2°C, ± 2%. All uncertainties are within 95% limits and account for errors in measurement, calibration, machining, and measuring devices. The water flow rate of the jet, Q_n, was 3 and 6 ℓ/min, measured with a flowmeter with a built in measurement error of ± 0.25 % and repeatability of ± 0.1%.

The plate temperature history during cooling was measured with thermocouples(11) inserted into the plate mounted aligned at distances of 0, 15, 35 and 55 mm, from the center of the 150 x 150 mm^2 plate. Grounded thermocouples K-type, 1.5 mm in sheath diameter made of 304 SS (the same as test plate) were inserted into by holes drilled from the bottom of the plate and placed 5 mm below the top plate surface. High temperature thermal paste with conductivity of 70 W/m.K was inserted into the hole to insure good thermal thermocouple-plate contact. The test plate was heated in furnace to the test temperature and transferred to the test position. The test temperature was 743°C. The water jet exit was set at a height H of 300 mm from the plate surface. The water jet temperature, T_j, was 12 and 27°C, measured using a K-type thermocouple (6) inside the header (12). A constant air temperature of 25°C was assumed. A digital camera was used to capture the images during the cooling process. Before each experiment, the impinging surface was sanded with 320 grit sandpaper and cleaned with acetone. The measured arithmetic mean roughness (Ra) at impingement zone surface, after quenching test, was found ranging 0.15 to 0.26 µm. For the new plate surface Ra = 0.11 µm.

For heat transfer behavior in water jet cooling analysis are needed some hydrodynamic parameters such as: the jet velocity at the nozzle exit (V_n), the impinging jet velocity (V_j), the impinging jet diameter (D_j) and the saturation temperature of water (T_{sat}) at the impingement zone. These parameters are listed in Tab. I and they were calculated using the equations of continuity and Bernoulli. The impinging jet velocity (V_j) by

$$V_j = \sqrt{V_n^2 + 2gH} \quad (1)$$

and the impinging jet diameter (D_j) by

$$D_j = D_n\sqrt{V_n/V_j} \quad (2)$$

the pressure at the stagnation point is given by

$$P_j = P_{atm} + (\rho_j . V_j^2)/2 \quad (3)$$

where D_n is the nozzle diameter, H is nozzle exit-to-plate surface distance equal to 300 mm, ρ_j is the mass density of water, P_j is stagnation pressure, P_{atm} is atmospheric pressure, and g is the gravitational acceleration. The jet velocity at nozzle exit, V_n, is calculated from $V_n = 4Q_n/(\pi.D_n^2)$. As the tests were carried out at an altitude above sea level of 234 m, the atmospheric pressure was around $P_{atm} \approx 97.2$ kPa. The stagnation pressure, P_j, represents the active pressure on top surface at the center of the plate (r = 0) where $P_j > P_{atm}$. The saturation temperature (T_{sat}) at r = 0 was found to be practically equal to 100°C. The saturation temperature, T_{sat}, must be carefully considered in water jet quenching cooling, because higher T_{sat} anticipate the change from nucleate boiling to the single-phase regime, contributing to an enhancement in the cooling capacity. For instance, in the hot strip mill cooling process $V_j \approx 7$ m/s and the T_{sat} rises to 105°C. Impinging water jet temperature (T_j) was 12 and 27°C, i.e. subcooling 88 and 74°C, respectively. Water jet subcooling (ΔT_{sub}) is given by $\Delta T_{sub} = T_{sat} - T_j$.

TABLE I. HYDRODYNAMIC PARAMETERS OF IMPINGING JET ON PLATE SURFACE AT STAGNATION POINT, R = 0.

Q_n (ℓ/min)	D_n (mm)	V_n (m/s)	D_j (mm)	V_j (m/s)	P_j (kPa)	T_{sat} (ºC)
3.0	10	0.6	5.1	2.5	101	100
6.0	10	1.3	6.8	2.7	101	100

A. *Inverse heat conduction analysis*

A commercial inverse heat conduction program, INTEMP, was used to predict the heat flux and temperature distribution along the cooling surface from temperature histories measured with thermocouples inserted in the test plate. INTEMP has been applied successfully in several jet quenching studies [22, 23]. INTEMP allows the thermal properties of material to vary with temperature in each finite element in order to avoid large errors in estimated heat flux and cooling surface temperature due to the assumption of constant thermal properties. INTEMP uses the dynamic programming method to solve the nonlinear inverse heat conduction problem with the finite element method. The methodologies of modeling and computations were detailed by Trujillo and Busby [24]. Two 2D axisymmetric finite element models were used for the numerical analysis. The model had a radius of 75 mm, 14 mm thickness and 4200 quadratic elements with 4-nodes per element for the plate 150 x 150 mm². Plate faces without impingement were considered adiabatic, since the radiation and free convective heat transfer rate are much smaller than that impinging side due to thermal insulation assembled. The top surface of the square plate of 150 x 150 mm² was divided into four zones with a uniform heat flux in each zone: $r_1 = 0$ to 7 mm (zone 1), $r_2 = 7$ to 25 mm (zone 2), $r_3 = 25$ to 45 mm (zone 3) and $r_4 = 45$ to 75 mm (zone 4). The tip of the all thermocouples were placed 5 mm below the top plate surface. The calculated relative uncertainty of the surface heat flux (q_s) is ± 5 %. The performance of this model was validated with the aid of commercial finite element analysis software, ANSYS. The thermal response for some typical known heat fluxes applied on plate surface was simulated by ANSYS model. The temperatures calculated by the ANSYS model were compared to those predicted by the INTEMP model. The mean disagreement found between these results was 0.1%.

III. RESULTS AND DISCUSSION

A. *Visual Analysis*

Fig. 2 shows the successive stages of the cooling process of the test plate at 743°C by a impinging water jet at $T_j = 27$ºC with flow rate (Q_n) of 6 ℓ/min. Immediately after the jet has collided (t = 0) with the hot surface, an insulating vapor blanket (film boiling) is formed and a white circle is observed under the jet. At t = 0.16 s, a small dark zone is formed, indicating that a stable solid-liquid contact was established and the surface is wetted. Around the wetted zone the surface still is dry covered by vapor blanket. Away from the center the surface remains dry and uncovered without vapor layer. The same observations were reported by Hatta et al. [15] who considered 10 mm-circular water jet at 20°C cooling of a 304 SS plate at 900°C.

During the cooling process, sputtering of small water droplets is formed in the frontier between wetted and dry zone. Over time, the wetted zone increases (t = 0.24 s), the sputtering water droplets increases, in the wetted-dry frontier, and reduction on the advance of wetted front velocity is observed. At t = 0.24 s, the wetted diameter was 20 mm, i.e. a radial advance of 10 mm with average velocity of 42 mm/s. From t = 0.24 to 3.00 s, the wetted diameter was 41.3 mm, a radial advance of only 11 mm and the velocity dropped to 4 mm/s. Agrawal et al. [25] also reported reduction on wetted front velocity for impinging water jet on steel surface heated at 800°C. This reduction in the velocity occurs because as the water moves radially outwards reduces its liquid layer thickness and receives heat from the hot surface, increasing its temperature. Thus, its ability to condense vapor bubbles is reduced. This analysis is in line with Karwa et al. [12] Lee et al. [14].

B. *Cooling Curves*

Fig. 3 shows the internal cooling temperature measured by thermocouples 1 to 4, at radial position r = 0, 15, 35 and 55 mm, for $T_i = 743$°C, with $Q_n = 3$ ℓ/min at 12ºC. No significant difference was observed among cooling curves until the onset of the water jet impingement on the hot steel plate at 743ºC and t = 19 s. Before jet cooling starts, the low cooling occurs by air convection and radiation. Few seconds before the onset of jet cooling, all the curves coincided,

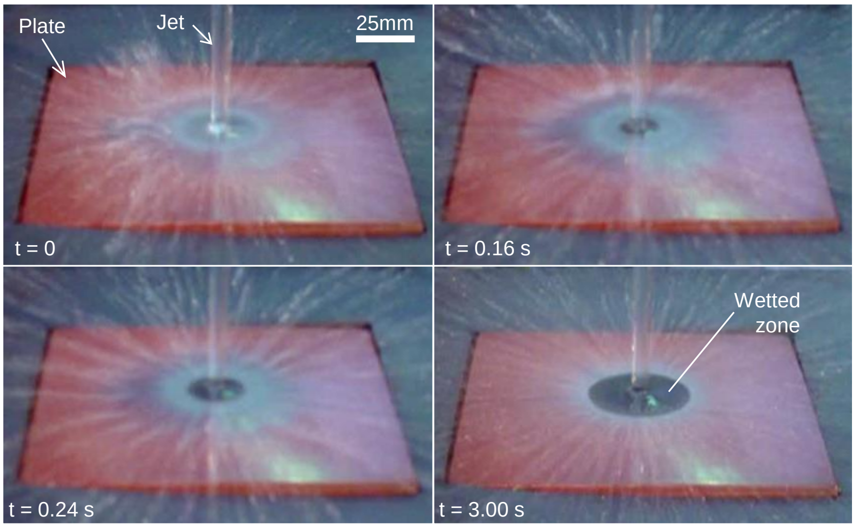

Fig. 2. *Successive stages of the cooling process for test plate at 743°C cooled by jet of 6 ℓ/min at 27 °C.*

indicating uniform temperature distribution in the test plate. After the jet hit the plate surface, temperatures dropped rapidly at radial position r = 0 (stagnation point). The next radial location of measurement, at r = 15 mm, cools down 1.5 s later. After the surface becomes wetted (see Fig. 2), the heat flux is enlarged and the temperature drop more evident at position r = 0 than other positions where hot surface remains dry. A remarkable increase in the cooling rate occurs at r = 35 and 55 mm, with the arrival of the wetted front.

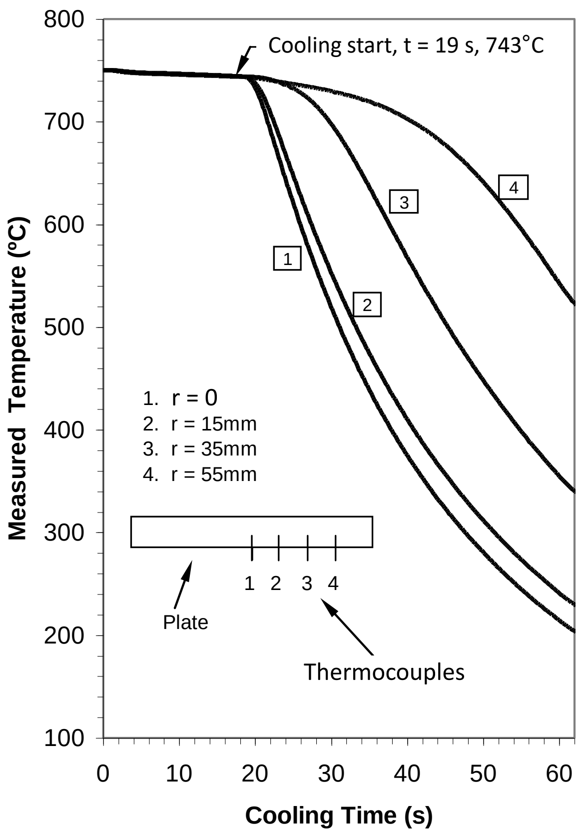

Fig. 3. *Measured internal temperatures at radial position r = 0, 15, 35 and 55 mm, for T_i = 743°C, with Q_n = 3 ℓ/min at 12ºC.*

Fig. 4 shows the comparison between calculated surface temperatures (T_s) from inverse heat conduction model (IHCM), and measured temperatures (T_m) for T_i = 743°C, r = 0 and Q_n = 3 ℓ/min at 12ºC. At t = 28 s, the surface temperature is T_s = 650°C while internally is T_m = 200°C. This shows the highly nonlinear temperature profile in the plate of 14 mm thick from a single jet cooling process.

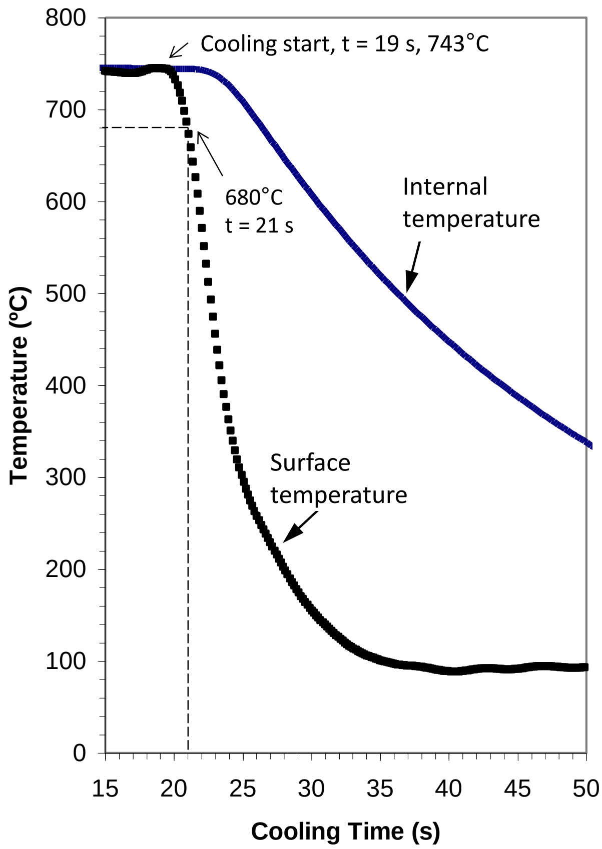

Fig. 4. *Comparison between calculated surface temperature and measured internal temperature at r = 0 for T_i = 743°C, with Q_n = 3 ℓ/min at 12ºC.*

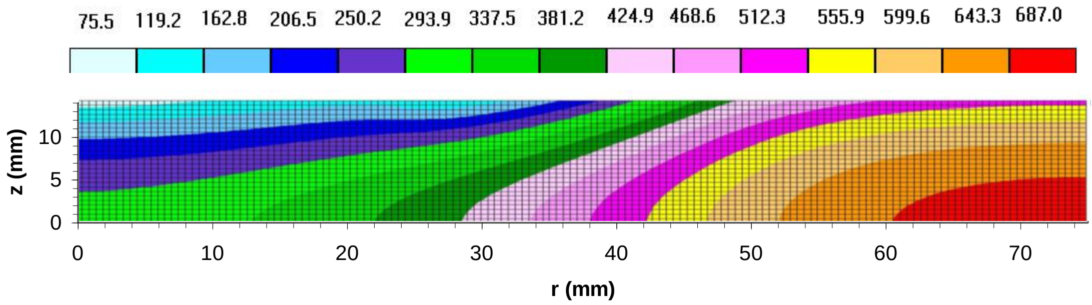

Fig. 5. *Isothermals 25 s after onset of the cooling process for a jet of 3ℓ/min at 12ºC.*

A dark zone (wetted zone) under the jet, similar to visualized in Fig. 2, was formed just after the jet hit the hot surface. Note that, 2 s (at t = 21 s) after the jet impingement the surface temperature is 680°C and, thus, the liquid water is in direct contact with such as high temperature beyond the critical point of water of 374°C. Several experimental works [15, 25, 14] of the jet cooling on hot steel reported the same elevated surface temperatures in wetted zone. Fig.5 shows isotherms at t = 25 s after onset of jet cooling process for T_i = 743°C with Q_n = 3 ℓ/min at 12ºC, where a strong thermal nonlinearity inside the plate is observed. At the stagnant point on surface, at r = 0 and y = 14 mm, the temperature is below 80°C while at r = 0 and y = 0, the temperature is above 290°C.

C. Boiling Curves

Boiling curves at radial positions r = 0, 15, 35, 55 mm, as function of time for T_i = 743°C with Q_n = 3 ℓ/min at 27ºC, is shown in Fig.6. For all radial positions, the surface heat flux is low before the jet impingement (t = 0 to 5 s). Once jet impinged, the hot surface becomes wetted and the heat flux (q) is enlarged more evident at position r = 0 (stagnation point) than other positions where the surface remains dry, reaching a peak of 3.45 MW/m². As wetted front arrives at each radial position, a peak of maximum heat flux occurs in each curve. However, the peaks decrease as they move away from r = 0, as for instance, the peak at r = 15 mm is 2.5 times lower than at r = 0. The reduction in the peaks is caused by the heating of water as moves radially outwards, reducing its heat removal capacity, as explained in section III-B. Agrawal et al. [25] reported similar trend for surface heat flux, during the impinging jet at 22°C on 800°C-steel surface, and that maximum heat flux decreases as the position moves away from the stagnation point (r = 0). Wang et al. [11] reported heat flux peaks decrease as they move away from r = 0, for a 4 mm-circular jet impinging (10°C) at 4.46 m/s on top of the hot steel plate (670°C), with similar heat fluxes values.

Fig.7 shows boiling curves at radial positions r = 0, 15, 35 mm, as function of surface temperature for T_i = 743°C with Q_n = 3 ℓ/min at 27ºC. At the onset of jet cooling process, the hot surface is covered by insulating vapor film and the heat flux is low. After wetting of surface, the heat flux is enlarged more evident at position r = 0 and reach its maximum value at surface around 200°C. At positions r = 15 and 35 mm also maximum heat flux occurs around 200°C, however with lower values than at r = 0 due to the reduction of heat removal capacity of water, as explained aforementioned. The heat flux increases with decreasing of surface temperature due to the vapor bubbles number reduction on the surface facilitating the liquid contact with surface.

D. Effect of Jet Subcooling

Fig.8 shows the effect of jet temperature (T_j), i.e. subcooling ($T_{sat} – T_j$), on boiling curves at r = 0 for a fixed Q_n = 3 ℓ/min at T_j = 12 and 27ºC as a function of time (Fig.8-a) and surface temperature (Fig.8-b). The curves (Fig.8-a) show that a lower jet temperature promotes a higher surface heat flux and reduces the delay for maximum heat flux (q_{max}) to be reached. For T_j = 12°C, the peak of 3.9 MW/m² occurred at t = 4 s, while for T_j = 27°C was 3.4 MW/m² at t = 5.5 s. Lee *et al.* [1] using a 304 SS plate heated at 750°C, water jet of 30°C, fixed Q_n = 3 ℓ/min found the maximum heat flux of 2.6 MW/m^2. Fig.8-b shows that a lower T_j allows q_{max} to be reached on higher surface temperatures, besides increasing q_{max}. For jet at 12°C, q_{max} = 3.9 MW/m² on surface at 240°C. For jet at 27°C, q_{max} = 3.4 MW/m² on surface at 165°C. The cooling intensity is remarkably enhanced when the water temperature is decreased Therefore, jet temperature is an important parameter to be considered in cooling control system for hot steel rolling, because promotes large and fast cooling rate in short time.

E. Effect of Flow Rate

Fig.9 shows the effect of water flow rate (Q_n) on boiling curves at r = 0 for Q_n = 3 and 6 ℓ/min at T_j = 27ºC as a function of time (Fig.9-a) and surface temperature (Fig.9-b). For 6 ℓ/min q_{max} = 3.9 MW/m^2 on surface at 250ºC, 14% higher than 3 ℓ/min, for a variation of 100% on Q_n, where q_{max} was 3.44 MW/m^2 on surface at 165ºC. An increase in Q_n reduces the delay for q_{max} to be reached, increases q_{max} which occurs on higher surface temperature.

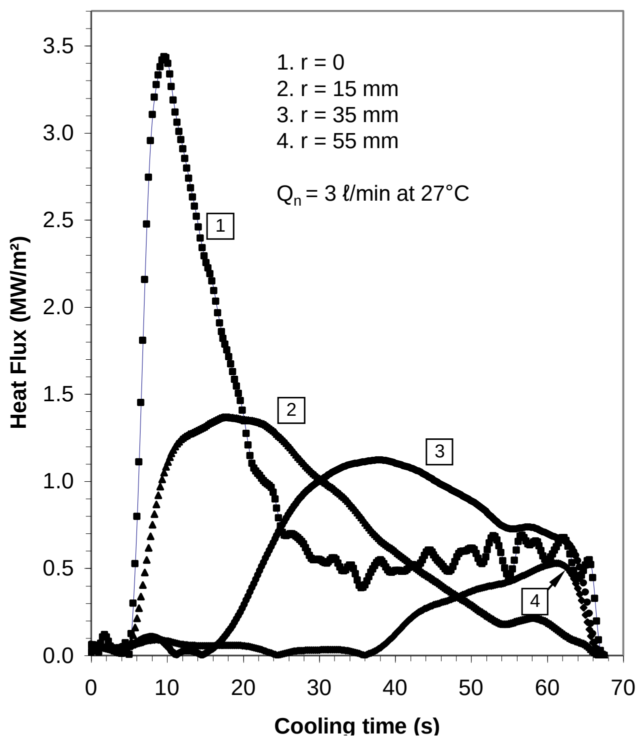

Fig. 6. *Surface heat flux curves as a function of time for at positions r = 0, 15, 35, 55 mm, for T_i = 743°C, with Q_n = 3 ℓ/min at 27°C.*

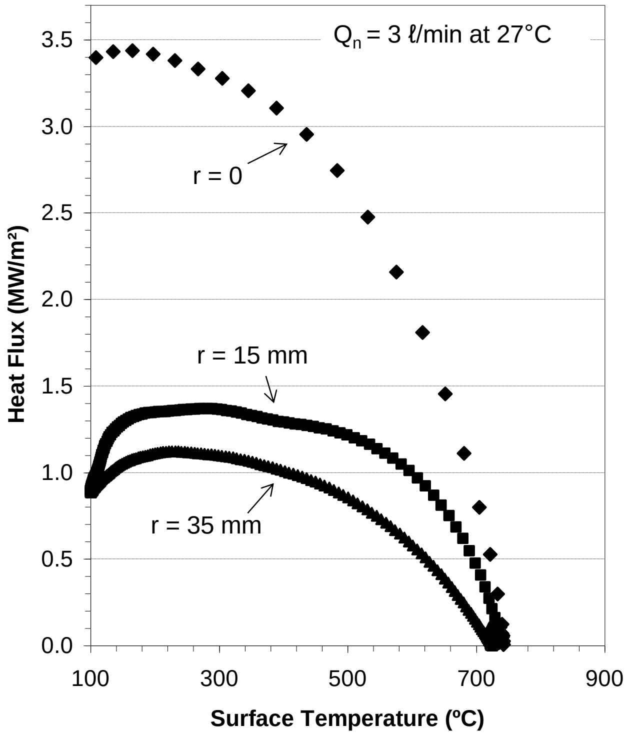

Fig. 7. *Heat flux curves as a function of surface temperature at positions r = 0, 15, 35, 55 mm, for T_i = 743°C, with Q_n = 3 ℓ/min at 27°C.*

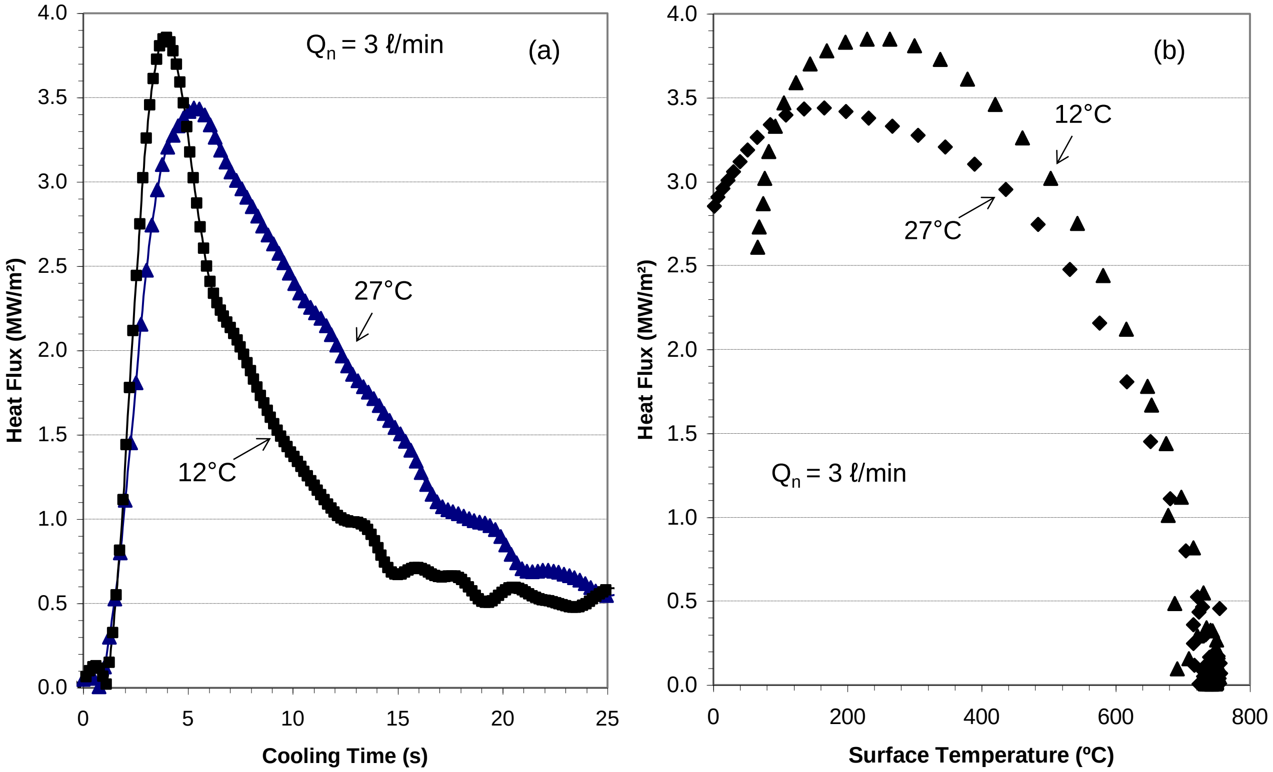

Fig. 8. *Heat fluxes curves at r = 0 with jet of 3ℓ/min at 12 and 27°C: (a) as a function of time and (b) as a function of surface temperature*

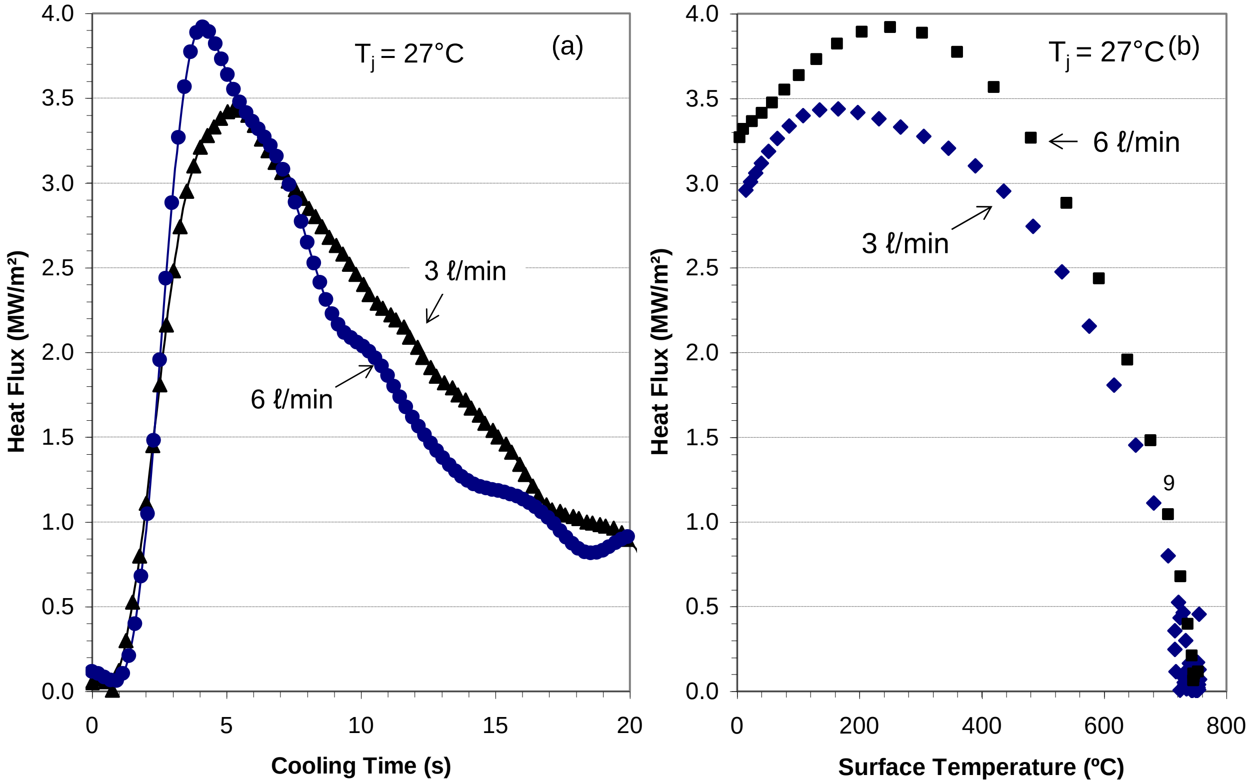

Fig. 9. *Heat fluxes curves at r = 0 with jet of 3 and 6 ℓ/min at 27°C: (a) as a function of time and (b) as a function of surface temperature.*

IV. Conclusions

The heat transfer characteristics of hot stainless steel plates during water jet impingement cooling have been successfully carried out with the help of an experimental apparatus. An inverse heat conduction model was used to predict the heat fluxes on top plate surface from measured temperatures into the plate. Temperature and water flow of the jet have a significant effect on the heat removal capacity in jet impingement zone. The surface heat flux increases with the reduction of jet temperatures. Higher water flow rate of the jet cause an increasing on cooling rate. The results would contribute to better understanding of the cooling control in steel industry and contribute for enhancement and designing of effective industrial ultra-fast cooling systems.

Acknowledgment

Author acknowledge the support from Usiminas Steel.

References

[1] P. Lee, H. Choi e S. Lee, “The Effect of Nozzle Height on Cooling Heat Transfer from a Hot Steel Plate by an Impinging Liquid Jet,” Iron and Steel Institute of Japan International, vol. 44, n. 4, p. 704–709, 2004.

[2] M. N. Hasan, M. Monde e Y. Mitsutake, “Homogeneous nucleation boiling during jet impingement quench of hot surfaces above thermodynamic limiting temperature,” International Journal of Heat and Mass Transfer, vol. 54, p. 2837–2843, 2011.

[3] J. Lee, S. Samanta and M. Steeper, "Review of accelerated cooling of steel plate," Ironmaking and Steelmaking, vol. 42, no. 4, 2015.

[4] C. Agrawal, "Surface Quenching by Jet Impingement - A Review," Steel research international, p. 1800285, 2018.

[5] J. Filipovic, F. P. Incropera e R. Viskanta, “Rewetting temperature and velocity in a quenching experiment,” Experimental Heat Transfer, vol. 8, n. 4, p. 257–270, 1995.

[6] S. D. Cox, S. J. Hardy e D. J. Parker, “Influence of Runout Table Operation Setup on Hot Strip Quality,” Ironmaking and Steelmaking, vol. 28, n. 5, pp. 363-372, 2001. https://doi.org/10.1179/irs.2001.28.5.363

[7] J. B. Wiskel, H. Deng, C. Jefferies and H. Henein, "Infrared thermography of TMCP microalloyed steel skelp at upcoiler and its application in quantifying laminar jet/skelp interaction," Ironmaking and Steelmaking, vol. 38, no. 1, pp. 35-42, 2011.

[8] J. Filipovic, R. Viskanta e F. Incropera, “Cooling of a Moving Steel Strip by an Array of Round Jets,” Steel Research, vol. 65, n. 12, pp. 541-547, 1994. https://doi.org/10.1002/srin.199401210

[9] P. J. Lee, M. Raudensky and J. Horsky, "Development of accelerated cooling for new plate mill," Ironmaking & Steelmaking, vol. 40, pp. 598-604, 2013.

[10] S. Sikdar and A. Mukhopadhyay, "Numerical determination of heat transfer coefficient for boiling phenomenon at runout table of hot strip mill," Ironmaking and Steelmaking, vol. 31, no. 6, pp. 495-502, 2004.

[11] B. Wang, D. Lin, Q. Xie, Z. Wang and G. Wang, "Heat transfer characteristics during jet impingement on a high-temperature plate surface," International Journal of Heat and Mass Transfer, vol. 101, p. 902–910, 2016.

[12] N. Karwa and P. Stephan, "Experimental investigation of free-surface jet impingement quenching process," International Journal of Heat and Mass Transfer, vol. 64, p. 1118–1126, 2013.

[13] Z. Wang, M. Zhong and J. Deng, "Experimental investigation on the transient film boiling heat transfer during quenching of FeCrAl," Annals of Nuclear Energy, vol. 150, p. 107842, 2021.

[14] S. G. Lee, M. Kaviany, C. Kim and L. Lee, "Quasi-steady front in quench subcooled-jet impingement boiling: Experiment and analysis," International Journal of Heat and Mass Transfer, vol. 113, p. 622–634, 2017.

[15] N. Hatta, J. Kokado e K. Hanasaki, "Numerical Analysis of Cooling Characteristics for Water Bar," Transactions ISIJ, vol. 23, pp. 555-564, 1983. https://doi.org/10.2355/isijinternational1966.23.555

[16] T. Ochi, S. NakanishI, M. Kaji e S. Ishigai, "Cooling of a hot plate with an impinging circular water jet," T. Veziroglu e A. Bergles, Eds., Amsterdam, Elsevier Science Publishers B.V., 1984, pp. 671-681. ISBN 0444423818, 9780444423818

[17] S. Ishigai, S. Nakanishi e T. Ochi, "Boiling heat transfer for a plane water jet impinging on a hot surface," em Proceedings 6th Int. Heat Transfer Conference, Toronto, Canada, 1978. DOI: 10.1615/IHTC6.860

[18] M. Prieto, L. Ruiz e J. Menendez, "Thermal performance of numerical hot strip mill runout table," Ironmaking and steelmaking, vol. 6, pp. 474-480, 2001.

[19] D. A. Zumbrunnen, F. Incropera e R. Viskanta, "A method and apparatus for measuring heat transfer distributions on moving and stationary plates cooled by a planar liquid jet," Experimental Thermal and Fluid Science, vol. 3, n. 2, pp. 202-213, 1990.

[20] W. Timm, K. Weinzierl and A. Leipertz, "Heat transfer in subcooled jet impingement boiling at high wall temperatures," International Journal of Heat and Mass Transfer, vol. 46, pp. 1385-1393, 2003.

[21] F. Xu e M. Gadala, "Heat transfer behavior in the impingement zone under circular water jet," International Journal of Heat and Mass Transfer, vol. 49, p. 3785–3799, 2006.

[22] N. Bhatt, R. Raj, P. Varshney e A. R. Pati, "Enhancement of heat transfer rate of high mass flux spray cooling by ethanol-water and ethanol-tween20-water solution at very high initial surface temperature," International Journal of Heat and Mass Transfer, vol. 110, pp. 330-347, 2017.

[23] S. V. Ravikumar, J. M. Jha, I. Sarkar, A. M. Tiara, S. K. Pal and S. Chakraborty, "Ultrafast cooling of medium carbon steel strip by air atomised water sprays with dissolved additives," Ironmaking and Steelmaking, vol. 41, no. 7, pp. 529-537, 2014.

[24] D. M. Trujillo e H. R. Busby, Practical Inverse Analysis in Engineering, Boca Raton: CRC Press, 1997. https://doi.org/10.1201/9780203710951

[25] C. Agrawal, R. Kumar and A. Gupta, "Rewetting and maximum surface heat flux during quenching of hot surface by round water jet impingement," International Journal of Heat and Mass Transfer, vol. 55, p. 4772–4782, 2012.