ANALYSIS OF THE COOLING EFFECT OF A WATER JET ON A HOT STEEL PLATE

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Abstract: *This study presents the results of the cooling process of a stagnant stainless steel plate of 150 x 150 mm² and 14 mm thickness by impinging circular water jets. The effect of the water temperature (12 and 26 ºC) and the flow rate (3 and 6 ℓ/min) were analyzed. The temperature history of the plate during the cooling process was measured with four thermocouples within the plate and these data were the enter data for the numerical analysis using the inverse heat conduction method to calculate the temperatures an the heat fluxes at the impinged surface and their history.*

Keywords: *Inverse heat conduction, Water jet cooling, Hot steel plate, Cooling effect, Heat transfer.*

1. INTRODUCTION

Free impinging jets of liquids on heated surfaces have been used in several industrial applications as a technique to transfer very high heat flux and also because the required simplest equipment (Lee *et al*, 2004). Runout table temperature control is one of the processes to obtain a particular mechanical properties of a steel strip employed in the (or by the ??) metal processing industry. Accelerated cooling has been implemented in hot strip mills to reduce the duration of this process, in order to achieve the required coiling temperature and to obtain the desirable grain structure (Cox *et al*, 2001; Devadas and Samarasekera, 1986; Evans *et al*, 1993; Guo, 1993 and Zumbrumen *et al*, 1989). In general, impinging circular water jets are used as a rapid cooling system for hot steel plates (Lee *et al*, 2004).

For a hot strip mill, conventionally, the finishing temperature (just after to exit the run-out table, before to form the coil) and the coiling temperature are in the range of 800-950°C and 510-750°C, respectively. In order to reduce the strip temperature at exit of last stand in the finishing train to coiling temperature, the strip is mainly cooled by the cooling water on the runout table. It includes heat conduction, single-phase forced convection, film, transition and nucleate boiling regimes, as is shown in Figure 1. Forced convection by the cooling medium represents more than 90% of the entire heat transfer and is still not fully understood because heat transfer mechanism involves a complex mixing phenomenon of water impingement and boiling on a moving surface (Guo, 1993; Lee *et al*, 2004; Liu and Samarasekera, 2002 and Filipovic *et al*, 1994). Guo (1993) concluded that 90% of the heat transfer in the process is governed by three mechanisms: single phase forced convection, nucleate boiling and film boiling.

In order to control the effective cooling process on runout table, it is important to evaluate, with accuracy, the heat transfer coefficient and the heat flux distribution as well their history along the length of the plate. Several experimental and numerical researches have been carried out on the subject to investigate water jet cooling (Hauksson *et al,* 2004; Hatta *et al*, 1984; Lee *et al*, 2004; Liu and Samarasekera, 2004; Mozumder *et al,* 2006; Packo *et al*, 1993; Xu and Gadala, 2006).

Even the important insights from these prior research works concerning the heat transfer mechanisms of water jet cooling on runout table the basic mechanisms are not well understood. The published results from different authors show disagreements between the values of heat flux for water cooling and also different magnitude orders of the heat transfer coefficients (5 to 100 kW/m²K), obtained by Hatta *et al*. (1984), Lee *et al. (*2004), Liu and Samarasekera (2004), Mozumder *et al* (2006), Packo *et al.* (1993) and Xu and Gadala (2006).

Filipovic *et al*. (1992, 1994) developed mathematical models for planar and circular impinging jets on a moving carbon steel plate and found that the increase of the subcooling (= $T_{sat} – T_w$), that represents the difference between the saturation and the jet temperatures, the heat flux increases, considerably, at the stagnation point. The same trend was found by Robidou *et al*. (2002), experimentally, for film and transition boiling regimes and the critical heat flux, for an impinging jet with rectangular cross sectional area of 1 x 9 mm² on a stainless steel plate.

Robidou *et al*. (2002) also found that the effect of the increase of the jet velocity from 0.7 to 0.8 m/s not produced a significant effect on the heat flux for all the boiling curve.

This work presents the preliminary results for the transient cooling process due to an impinging water jet on a

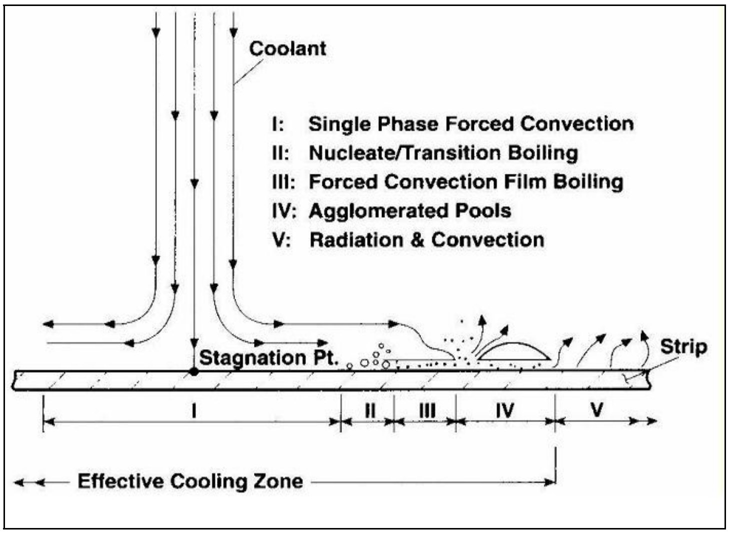


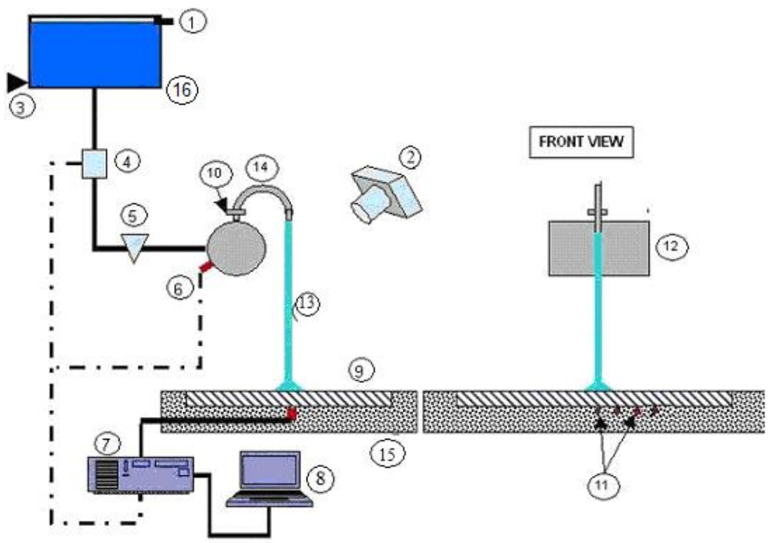
Figure 1: Heat transfer regimes adjacent to a jet impinging on hot strip (Zumbrumen *et al*, 1989).

hot steel plate at 1,013K. The analysis involves the measurements of the temperature in four aligned points inside the plate, at the same deep: one at the center line of the impinging jet and the others distant far from the center. By means the measured temperatures, a two-dimensional symmetrical-axis finite element method, based on the transient inverse heat conduction model, was used to back-calculate the local and instantaneous heat flux and heat transfer coefficient along the impinged surface plate. The objective of this study is to try to understand the main mechanisms of the cooling process as function of two water flow rates and two temperatures of the water jet.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

2.1. Experimental Facilities

Figure 2 shows the outline of the experimental facilities installed at the Research Center of USIMINAS Steel Work plant, in Ipatinga-MG-Brazil. The coolant fluid is the ordinary city water stored in a tank (16), whose the equivalent pressure head is 7 m, allowing an exit flow jet (13) at the U-tube (14) existing at the end of an U-tube (curvature radius of 70 mm), whose the inner diameter is 10 mm.



1. Overflow tube
2. Digital camera
3. Water supply
4. Flow meter
5. Globe valve
6. Thermocouple
7. Recorder
8. Computer
9. Test steel plate
10. Union
11. K-type thermocouples
12. Header
13. Water jet
14. Hair pin nozzle
15. Insulation
16. Water tank

Figure 2: Outline of the experimental apparatus

The reason for using the U-tube is that the water from the nozzle is believed to be in the state of a stable flow without including air at the nozzle exit and to be compatible with those used in the steel industry. The overflow tube (1) has the function to keep constant the water level in the water tank (16), assuring a constant pressure in the U-tube (14).

A test section (a stainless steel plate) (9) was heated until the test temperature in a 75 kW electrical furnace with 800 mm wide, 1000 mm long and 600 mm high which has the ability of heating up to 1300°C. The plate material is the AISI 304 (18-8 stainless steel) in order to prevent oxidation and phase transformation during the cooling process, as this can occurs with the carbon steel causing the change. The square plate was 150x150 mm^2 and 14 mm thickness. Table 1 shows some properties of the AISI 304 for temperatures between 27 and 927^{o}C (Peckner and Bernstein, 1977; Incropera and De Witt, 2003; Melo *et al*., 2005).

The thermal conductivity of the insulation (15), ceramic fiber board (alumina and silica), in contact with the four end sides and bottom of the plate was of 0.17 and 0.078 W/mK, at 1090°C and 540°C, respectively, with dimensions of 350 x 350 mm^2 and 50 mm thickness.

The data acquisition system, with 10 channels, allows a rate acquisition of 10 points per second.

Two water flow rates were tested: 3 and 6 ℓ/min, with ± 0.25% of uncertainty.

Table 1: Thermo-physical properties for the AISI 304 stainless steel

T(°C)	c_p(J/kgK)	ρ(kg/m^3)	k(W/mK)
27	447	8000	15.2
127	515	7958	16.6
327	557	7874	19.8
527	582	7790	22.6
727	611	7705	25.4
927	640	7619	28.0

2.2. Experimental Procedure

The temperature history of the plate during the cooling process was measured with four thermocouples installed on the opposite side to the jet's impingement. The 1.5-mm diameter sheathed K-type thermocouples were mounted aligned at distances r of 0, 0.015, 0.035 and 0.055 m of the impingement point, in r=0, and at z=5 mm of deep. The plate surface was cleaned with ethanol and heated, up to 900°C in the electrical furnace. Once the measured temperature of the steel plate reached 900°C, it was kept in the furnace for more 30 min in order to allow the plate being uniformly heated to 900°C before to be withdrawn from the furnace and transferred to the test position. The temperature of the plate, before to start the cooling process by the impinging water jet, was near of 740°C because the heat losses to the ambient air by natural convection.

The height from the top nozzle exit to the test plate, H, was adjusted at 300mm. In the case of a very small water flow rate, the distance H could not be so largely extended, because the water bar from the nozzle exit was broken on the way to the plate surface. Hatta *et al*. (1983) and Lee *et al.* (2004) had shown that the effect of the height nozzle H influences weakly in the cooling curve at the stagnation point when a continuous jet is maintained.

Two water temperatures were tested: 12°C and 26°C, measured using a K-type thermocouple in the header. The water temperature of 12°C was kept using ice in fusing and for 26°C was normal temperature of ordinary city water.

A digital camera was employed to capture the images during cooling process with 13 photographs per second.

In order to analyze the heat transfer behavior, we need several hydrodynamic parameters besides the processing ones: jet velocity, jet diameter and saturation temperature of water. These parameters are listed in the Table 2 and the following equations are used to calculate them. The jet velocity (also called impact velocity) with which water vertically hits the plate can be calculated by

$$V_j = \sqrt{V_n^2 + 2gH} \tag{1}$$

where V_j and V_n are the jet velocity and the water velocity at nozzle exit, in m/s, respectivly; g is the acceleration due to gravity, in m/s^2; and H is the vertical distance from nozzle exit to the plate surface, in m.

The diameter of water jet D_j is calculated by:

$$D_j = D_n \sqrt{V_n / V_j} \tag{2}$$

where D_n is the nozzle diameter.

The pressure at the stagnation point is given by

$$P_s = P_a + \frac{1}{2}\rho V_j^2 \quad (3)$$

where P_a = 95.15kPa is the atmospheric pressure at USIMINAS Steel and ρ is the density of water. The saturation temperature T_{sat} can be obtained from the saturation table of water according to the pressure.

The accelerated cooling process, in hot strip mill, the V_j is around 6.5m/s, which the saturation temperature is 103.7ºC for Ps= 115.8kPa.

Table 2: Hydrodynamic parameters at stagnation point

Q_w (ℓ/min)	D_n (mm)	V_n, (m/s)	D_j (mm)	V_j (m/s)	P_s (kPa)	T_{sat} (ºC)
3.0	10	0.64	5.1	2.5	98.3	98.7
6.0	10	1.27	6.9	2.7	98.8	99.0

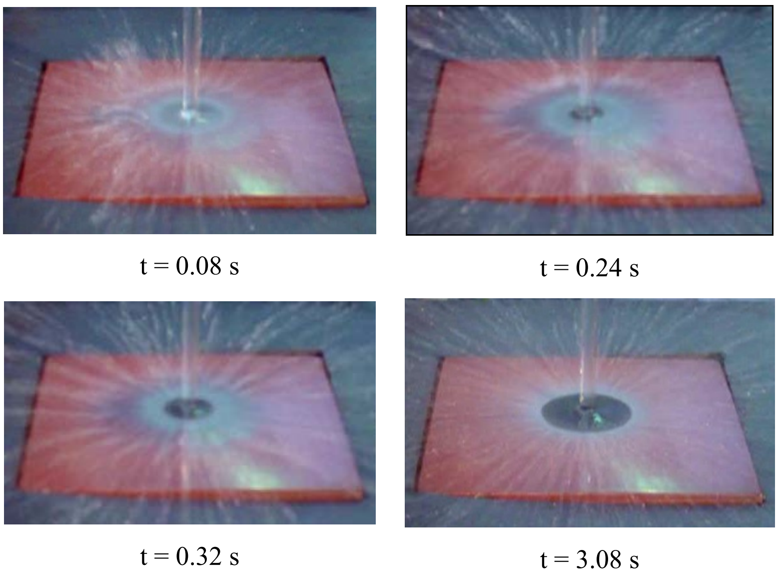
2.3. Numerical Inverse Heat Transfer Analysis

An inverse conduction heat transfer analysis was carried out by using the solver developed by Trujillo (2003), in order to calculate the extrapolated temperature and the heat flux on the impinging surface from the measured hot plate temperatures. For the numerical tests, a 2D axisymmetric finite element model has been used. The model has 75 mm radius, 14 mm thickness and 4200 quadratic elements with 4-nodes per element. The data are input as the temperature-time histories at number of nodes which corresponds with the location of the thermocouples installed inside the test. The top surface is divided into four regions with uniform heat flux in each region: r_1 = 0 to 0.007 m, r_2 = 0.007 to 0.025 m, r_3 = 0.025 to 0.045m and r_4 = 0.045 to 0.075m. The software then solves for the unknown flux-time histories for these four regions specified. For boundary conditions, an adiabatic condition was used on the sides of the plate without impingement, since the radiative and free convective heat transfer quantities on those surfaces are much less than the boiling heat transfer quantity on the impinging side.

3. RESULTS AND DISCUSSION

3.1. Visualization

Figure 3 shows a sequence of four photographs, during the cooling process, with a flow rate of 6 ℓ/min and the water temperature of 26ºC and the initial plate temperature of 740ºC. Because slow velocity of the digital camera, 13 frames/s, and the uncertainty on the synchronism of the jet discharge and the turn on of the digital camera, the instant when the water jet touch the plate is uncertain, occurring in the interval between 0 and 0.08 s. After the beginning of the cooling process, there is the formation of a small white circle, near the center of impinging jet. Once this circle is disappeared, a circular single-phase forced convection area is developed. During the cooling process, sputtering of small water droplets, caused by boiling, was observed on the circular boundary of the forced convection area. Because the boiling intensity decreases during as cooling progresses, the size of the sputtering water droplets increases and the intensity of the sputtering decreases.



t = 0.08 s

t = 0.24 s

t = 0.32 s

t = 3.08 s

Figure 3: Photographs of the plate for the 3.08 s of the cooling process, water at 26ºC and 6 ℓ/min.

3.2. Cooling Curves

Figure 4-a shows four temperature history curves obtained with the thermocouples 1 to 4, at r=0, 15, 35 and 55 mm, for water flow rate and temperature of 3 l/min (0.64 m/s) and 12°C, respectively, and the distance *H* of 300 mm. The water jet begins to impinge on the hot steel plate at 743ºC and 19 s. Before the water jet was turned on, the four thermocouples measured the same temperatures that shows the uniformity of the temperature at the same z. After the jet to hit the plate surface the temperature decreases rapidly at stagnation point and with a delay of few seconds at 15 mm from the centre.

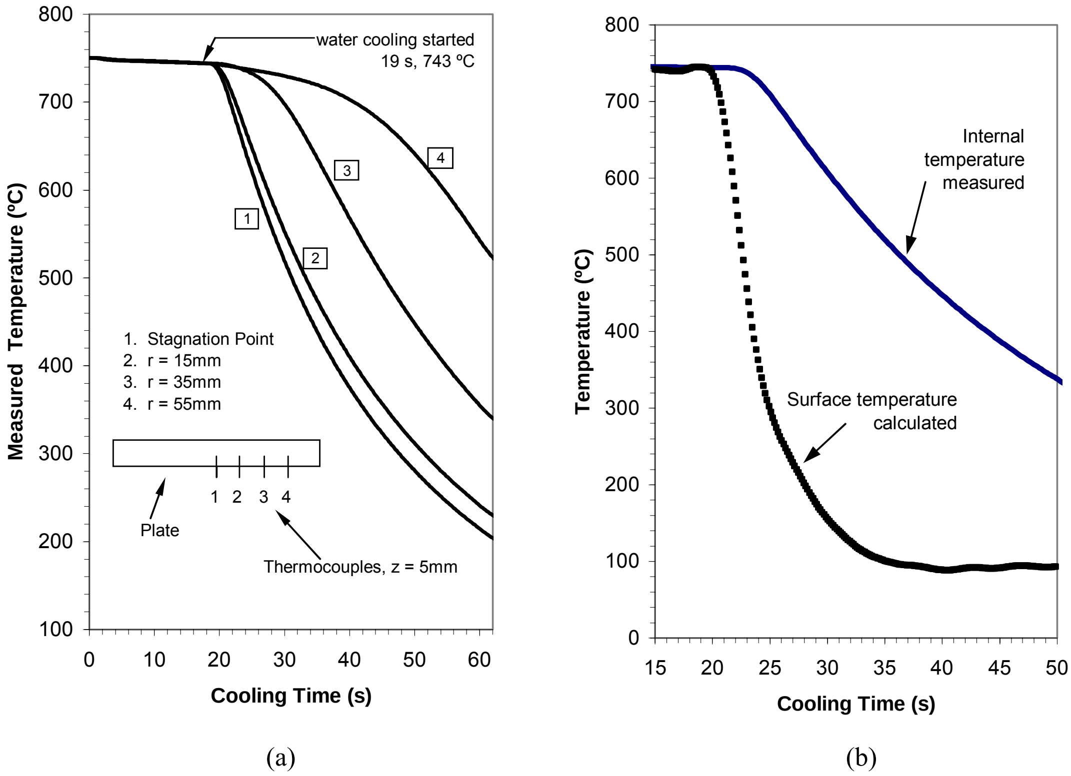


Figure 4: (a) Measured internal temperatures for 3ℓ/min and 12ºC at *r* positions the radial distance from centre of the plate; (b) Calculated surface temperature and measured internal temperature, at *r* = 15mm and z = 5mm from stagnation point for 3ℓ/min and 12ºC.

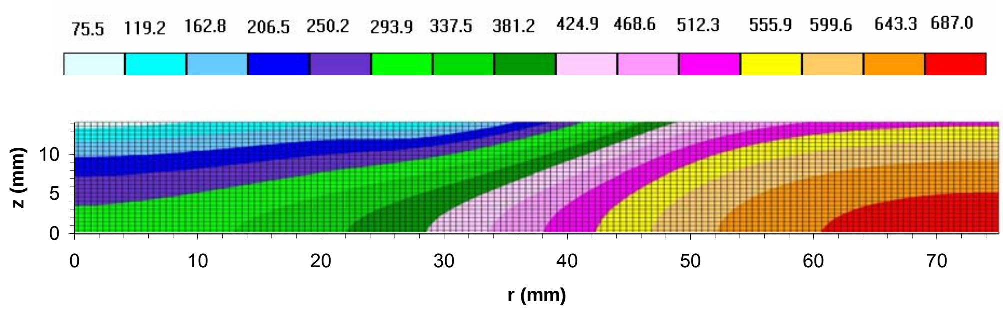


Figure 5: Isothermals at 25 s after start cooling process for 3ℓ/min and 12ºC

Figure 4-b shows cooling curves for calculated surface temperature and measured internal temperature at one location of measurement inside the impingement zone, at *r*=15 mm, for 3ℓ/min and 12ºC. It can be observed that the surface temperature drops much faster than the internal temperature in the first few seconds of the cooling process, which indicates that the temperature profile in the plate during this period is highly nonlinear. Similar trends to these were seen in data from all tests. Figure 5 shows the corresponding distribution of isothermals at 25 s after to start cooling process.

3.3. Partial Boiling Curves

Figure 6-a shows the instantaneous heat flux calculated for the impinged surface of the plate for a water jet of 3ℓ/min and 26ºC, considering the measured points of temperature. The comparison of the peaks of these curves shows that this one for the curve 1 (within the stagnation point) is significantly higher than this one for the other curves. The maximum heat flux for the curve 2 is of about a half for this one of curve 1. The same trends were reported by Hauksson *et al*. (2004). Figure 6-b shows the partial boiling curves for r=0, 15 mm and 35 mm.

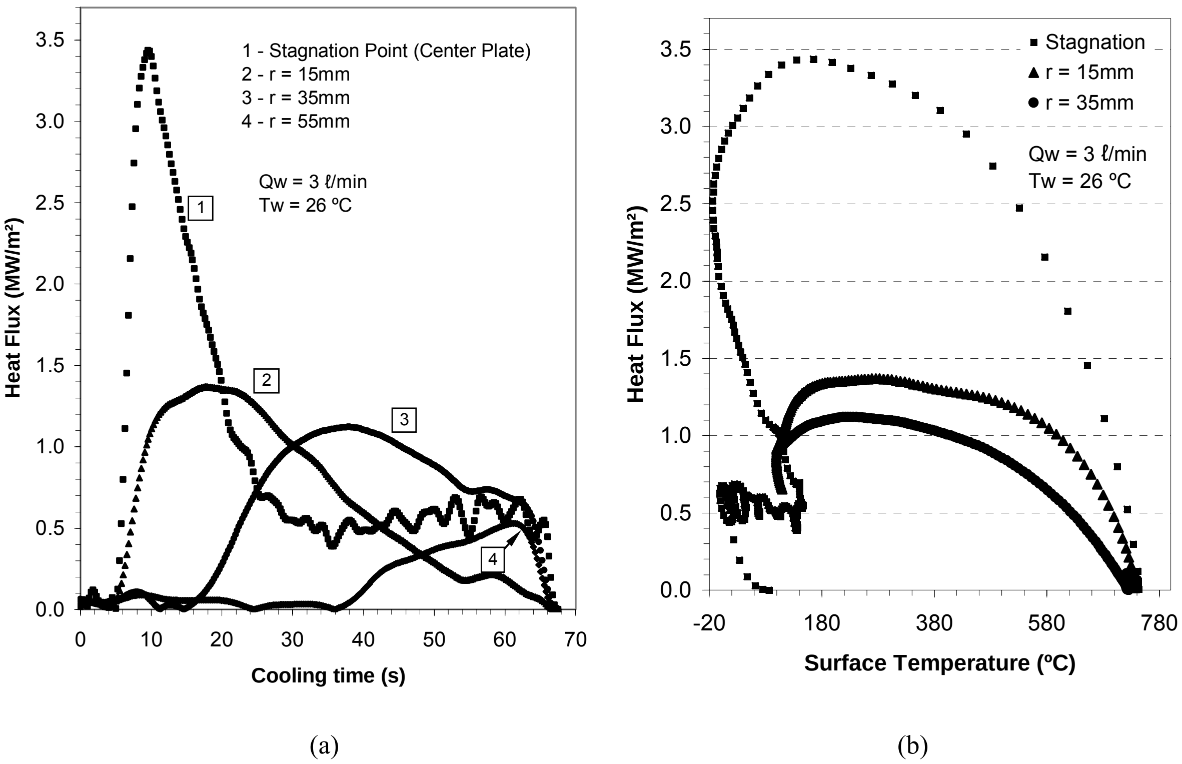


Figure 6: (a) Surface heat fluxes at given locations as function of time; (b) Boiling curves as function of surface temperature for r=0, 15 mm and 35 mm.

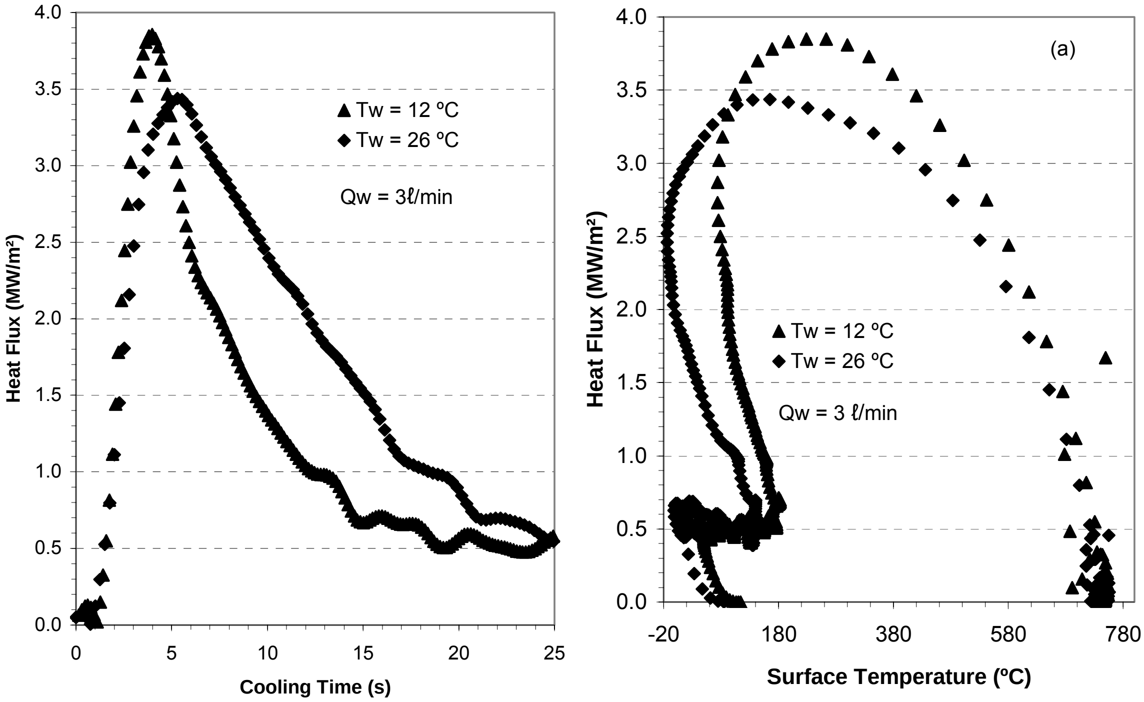
Figures 6b shows that the maximum heat flux is shifted to the left, that corresponds to smaller values of ΔT_{sat} (that represents the wall superheat: the difference between the surface and the water saturation temperatures) with the increase of the distance from the stagnation point. This trend was also observed for all the tests.

The initial stage of the cooling process, until the maximum value of heat flux is reached, is obviously characterized by the film and transition boiling regimes, as is supported by the visual observations. This agrees with the results obtained by Kokado *et al* (1984). The transition boiling regime is characterized as an intermittent succession of nucleate and film boiling.

The second peak of the boiling curve, located outside of the stagnation point was a repeated result for all the tests, in this work. It is considered, also, in the transition boiling regime.

3.4. Effect of subcooling

Figure 7-a shows partial local boiling curves, the surface heat flux as function of surface temperature, at the stagnation point, for a 3 l/min (0.64 m/s) jet water and for two temperatures, 12 and 26ºC. These two curves coincide during the first 3 s of the cooling process, as is shown in the Fig. 7b, that corresponds to the film boiling regime, because the high surface temperatures. For heat fluxes higher than 2 MW/m^2 and until to the peak of the curves, the local heat flux increases with the increase of the subcooling, or the decrease of the water temperature, corresponding to the transition boiling regime. After the peak heat flux, the heat transfer regime is the nucleate boiling until the heat flux of 0.7 MW/m^2, Fig. 7b, when the heat transfer mode is the single phase forced convection. The maximum heat flux was 3.85 MW/m^2 for 12°C, or 11% higher than the local maximum heat flux for the water at 26°C. The maximum heat flux occurs at wall superheating around 160 and 240ºC for the water jet at 26 and 12ºC, respectively. These results are coherent with the literature trend and Liu *et al*. (2002) found the maximum heat flux of 7.5 MW/m^2, with 450°C for the surface temperature of a stainless steel plate (AISI 316L), whose the beginning temperature was 900°C, and water flow rate of 60 ℓ/min and temperature of 30°C. Lee *et al*. (2004) using an AISI 304 plate, whose the beginning temperature was 750°C, and water temperature of 30°C and flow rate of 3ℓ/min for nozzle height *H* varying from 0.04m to 0.45m found the maximum heat flux of 2.6 MW/m^2.

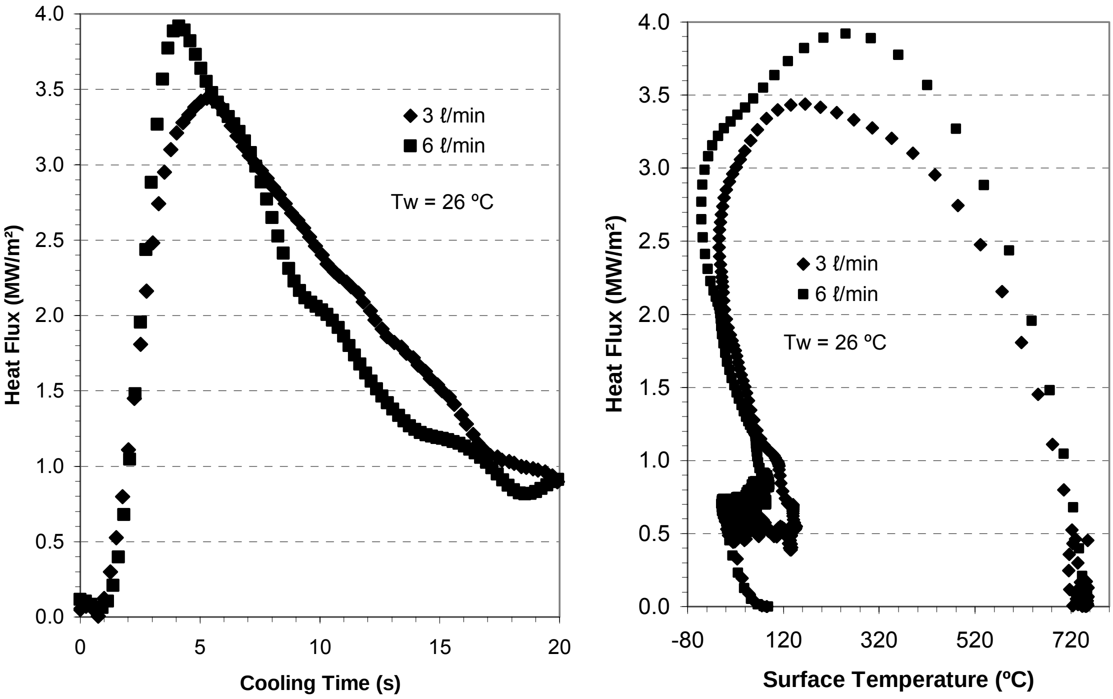


(a) (b)

Figure 7: Effect of the water temperature. (a) Partial boiling curve; (b) Surface heat flux history.

3.5. Effect of the water flow rate

Figure 8a-b shows the results for the effect of the flow rate, for water temperature of 26°C. A similar trend, qualitatively and quantitatively, of the effect of the increase of the subcooling was found when the flow rate increases from 3 to 6 ℓ/min. The maximum heat flux was 3.92 MW/m^2 for 6 ℓ/min, 14% higher than the heat flux for 3 ℓ/min.



(a) (b)

Figure 8: Effect of the flow rate, at r=0, with T_w=26^{o}C. (a) Partial boiling curve; (b) Surface heat flux history.

3.6. Discussion

The shape of the boiling curve obtained by the numerical inverse heat transfer analysis, in this study, is very different of the classical one for a boiling process in a pool boiling, as reported by Carey (1992), and also from this ones reported by Robidou *et al*. (2002). In the above section was considered that the cooling process, at the stagnation point, was due to the transition boiling regime, unlike the schematic description of mechanisms in Figure 1. The second strange result concerns the high surface temperature for the beginning of the transition boiling. These doubts not yet answered in this preliminary work needs to be considered in the continuation of this research.

4. CONCLUSION

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. A two dimensional finite element method based inverse heat conduction model using iterative and sequential regularization method was used to calculate the heat fluxes along the surface of the plate. The input to the numerical model and its validation was the temperature data measured by four thermocouples within the plate, at z=5 mm. The following conclusions can be drawn from this study:

The subcooling increase of 14^{o}C and the increase of the flow rate from 3 to 6 ℓ/min in the water jet presented the same effect to increase the heat flux at the stagnation point.

The cooling rates and the heat fluxes calculated for the first measuring location (stagnation point) is significantly higher than for all the other locations and the cooling process starts earlier.

The maximum heat flux occurs for wall superheating around 160 and 240ºC, for all test conditions of this study.

5. AKNOWLEDGEMENTS

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