LOCAL HEAT TRANSFER ANALYSIS DURING INTENSIVE COOLING WITH WATER SPRAYS AND JETS

Fang Y.*, and Specht E.
*Author for correspondence
Chair of Thermodynamics and Combustion,
Otto von Guericke University,
Magdeburg, 39106,
Germany,
E-mail: m_yuanfang@hotmail.com

ABSTRACT

The heat transfer during the cooling of heated metals by using sprays and jets is experimentally investigated. The investigations concern spray, full jet and flat jet nozzle as well as a nozzle field made of full jet nozzles. The metal samples are heated in an oven to 850 °C and then quenched in a cooling chamber by different type of nozzles. During the cooling process, the temperature of the cooled metal is measured with an infrared camera.

A significant result of the experimental investigations is the concrete proof of the influence of technical parameters such as the initial temperature, jet velocity, jet diameter, metal type, etc. on DNB, rewetting temperature, heat transfer and the progress of the wetting front.

INTRODUCTION

In many industrial heat treatment plants, cooling of hot metals with various nozzles or their combinations can be found. In order to achieve required material properties, cooling rates up to a high extent have to be fulfilled. At the same time, care must be taken to ensure that the cooling process is precisely controlled so that thermal stresses and distortions are minimised and furthermore totally removed. The investigations focused on full jet, flat jet and spray nozzle as well as jet fields made of full jet nozzles as shown in Figure 1.

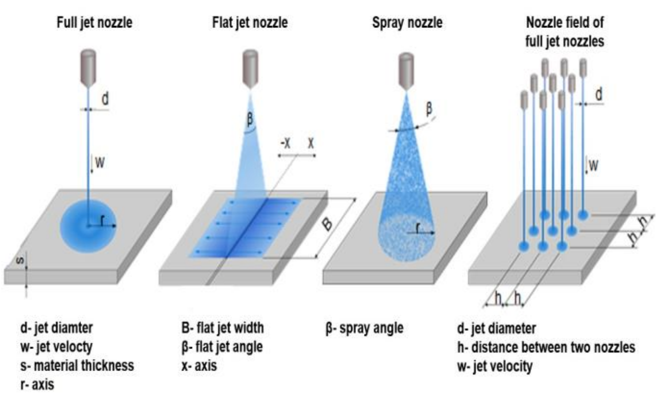

Figure 1 Schematics of investigated nozzle types

The full jet nozzle is characterized by a free water jet with a certain jet length and diameter *d*, which strikes onto the hot surface with a velocity *w*. Meanwhile, the liquid jet experiences an expansion before the impact occurs. In the case of flat jet nozzle, the liquid jet is widened at a certain angle β at the nozzle exit. It then impinges with a width *B* on the surface to be cooled. The spray nozzle produces a spray of fine droplets at the nozzle outlet which spreads out in a conical shape with a certain angle. The feature for the spray nozzle is that, when the spray strikes the surface to be cooled, initially there is no complete wetting of the hot surface. This is the main difference to full jet and flat jet nozzle. The full jet concentrates at the shooting point, while the flat jet is characterized by a rectangular propagation in two opposing directions. The full jet and flat jet nozzles are usually used when an intensive cooling of hot metals has to be achieved. If a relative lower cooling rate is needed, spray nozzles are frequently used. Basic work on the investigation of the cooling of full jets is based on Monde et al. [1, 2]. In their work, the temperature is measured with thermocouples. However, the local resolution of the temperature measurements in the radial direction encounter limitations, since the thermocouples cannot be placed exactly next to each other. This is particularly important in the wetting front since temperature gradients above 100 °C/mm can occur. For this reason, current work has been focusing on the non-contact temperature measurement of surface temperatures by means of infrared thermography. In this context, reference is made to dissertations [3, 4, 5, 6]. In the literature for the cooling of metals, contributions to the application of infrared thermography have been published since 2012 [7, 8, 9].

NOMENCLATURE

B	[mm]	Width of flat jet
d	[mm]	Jet diamter
H	[mm]	Nozzle spacing
s	[mm]	Sample thickness
$\dot{V}$	[l/min]	Volume flow rate
w	[m/s]	Jet velocity
Greek symbols		
α	[°]	Nozzle angle
β	[°]	Jet or spray angle
Subscripts		
w		water
0		Initial

EXPERIMENTAL INVESTIGATIONS

The principle of experimental investigations is shown in Figure 2. A metal sample heated to an initial temperature T_0 with the thickness *s* is sprayed with either single nozzle or a nozzle field. The temperature field is then measured at the rear surface of the metal plate. For the purpose of the accuracy the thermal image was captured and stored at the extremely high frame rate of 150 images per second within the range of 240 × 80 pixels. The accuracy of ambient temperature measurement has the uncertainty of ±1 °C. The distance between camera lens and plate surface has an error of ±0.5 cm. The emissivity of the plate surface with black paint is measured with an uncertainty of ±0.02. The temporal and local temperature histories are the basic values for determining parameters which are interested. The following technical parameters influence the heat transfer and therefore have been varied in experiments:

- Jet velocity w
- Jet diameter d
- Nozzle angle α
- Nozzle spacing H
- Initial temperature T_0
- Plate thickness s
- Metal type

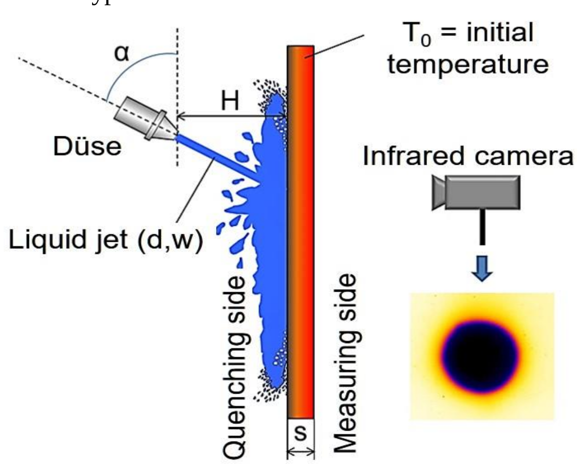

Figure 2 Principle of experimental investigations

For flat jet and spray nozzles, it is not possible to define the velocities. Hence, the volume flow rate is used as characteristic parameter. An important factor influencing the spray is the impingement density and its local distribution. The impingement density was measured with a patternator, which consists of brass tubes with diameters of 10 mm by changing the distance. The impingement density can then be derived from $\dot{m} = m_d /(A\Delta t)$ where m_d is the mass of the water droplets collected, *A* is the area of the opening of the tube and Δt is the measurement period. The measurement was estimated to be accurate within ±4% as several repeating measurements were fluctuating in this range.

Based on the measurements from infrared camera, an analytical inverse approach is utilised in order to determine the rewetting temperature, the DNB temperature, the propagation of the wetting front, and temperature and heat flux on quenching side.

RESULTS OF FULL JET NOZZLE

When the full jet nozzle is applied in the quenching experiments, the infrared images show visually that concentric low temperature contours spread out from the shooting point and then uniformly move outwards. The surface near the shooting point is immediately wetted, in which a longer film boiling regime is unlikely to be attained. This is also shown by the rewetting temperatures shown in Figure 3. These temperatures indicate the surface temperature at which the wetting front is formed. Below this temperature, the metal is wetted, and vice versa. A rewetting temperature cannot be detected below a radius of approximately 7 mm, since an immediate rewetting takes place there. A strong dependency of the rewetting temperature on initial temperature can be found for the full jet nozzles with orifice diameter from 0.8 to 2.7 mm. The corresponding jet velocity at the nozzle outlet ranges from 10 und 28 m/s. The influence of the diameter d of the nozzle and the jet velocity *w* on the rewetting temperature are insignificant according to Figure 3.

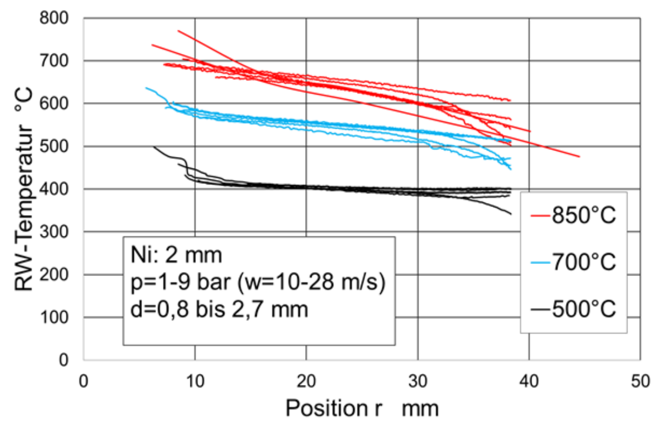

Figure 3 Rewetting temperature for nickel plate at different initial temperatures

Figure 4 shows the rewetting temperature for 4 metal types at a nozzle pressure 5 bar and an initial temperature 500 °C. The values of the individual metals are similar and grouped around the results of standard metal nickel used in the investigations. A slight increase is to be found with decreasing heat penetration coefficient b. The Aluminium alloy has the smallest values and the stainless alloy Nicrofer the largest. In practical applications, an average value from the investigated metals can be used. This behaviour does not change when the rewetting temperature is considered at a nozzle pressure of 9 bar, which corresponds to a jet velocity of 26 m/s.

The DNB temperature is the surface temperature at which the heat flux reaches a maximum value. Below this temperature, it is the regime of the nucleate boiling; above this value to rewetting temperature, heat transfer mechanism is designated transition boiling. Figure 5 shows the DNB temperatures for initial temperature of 500 ° C and 850 ° C, respectively.

The DNB temperature is the surface temperature at which the heat flux reaches a maximum value. Below this temperature, it is the regime of the nucleate boiling; above this value to rewetting temperature, heat transfer mechanism is designated

transition boiling. Figure 5 shows the DNB temperatures for initial temperature of 500 ° C and 850 ° C, respectively.

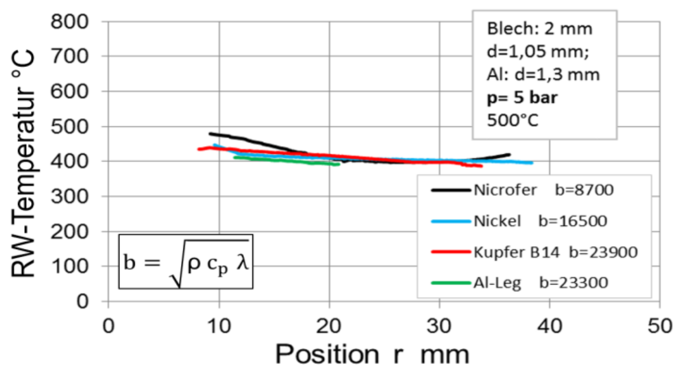

Figure 4 Rewetting temperature for different metals

The DNB temperature is the surface temperature at which the heat flux reaches a maximum value. Below this temperature, it is the regime of the nucleate boiling; above this value to rewetting temperature, heat transfer mechanism is designated transition boiling. Figure 5 shows the DNB temperatures for initial temperature of 500 ° C and 850 ° C, respectively.

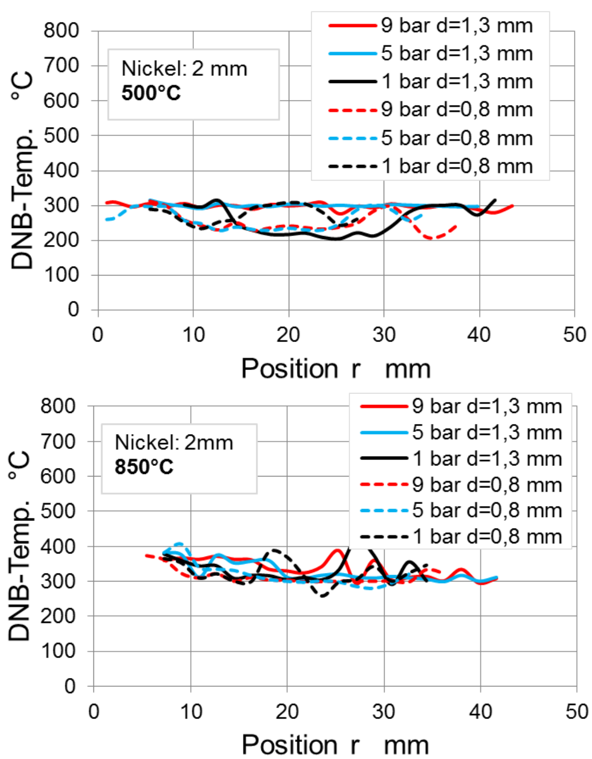

Figure 5 DNB temperature at two initial temperatures

The DNB temperatures determined from the measured temperature profiles have a relatively large fluctuation distributed over the radius. The value is around 300 °C for an initial temperature of 500 °C. An increase in the DNB temperature is also observed with increasing initial temperature.

Figure 6 shows the heat flux as a function of the surface temperature of a nickel plate cooled with a full jet nozzle at an initial temperature of 850 ° C. The maximum of the curves stays around 350 °C. This corresponds to the DNB temperature which is shown in Figure 5.

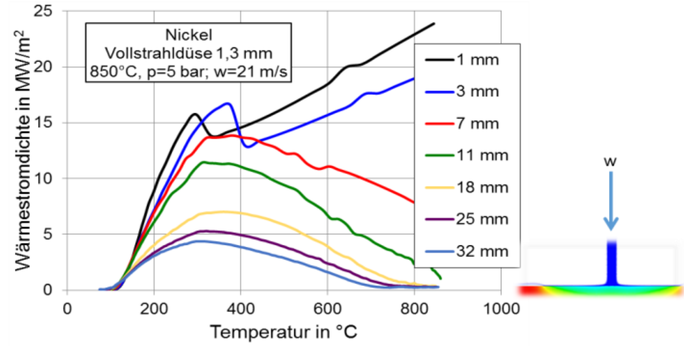

Figure 6 Boiling curves for nickel with a full jet nozzle

In the region near the impingement point of the full jet, there is no global maximum for radial distances of r = 1 to 3 mm. This means that there is no film boiling, since the impact of the water jet immediately initiates a very high heat transfer rate. At a distance from the impingement point of 11 mm, the heat flux reaches the maximum value of approximately 12 MW/m^2. As the distance from impingement point increases, the heat flux decreases further and reaches a value of approximately 4 MW/m^2 at a radius of 32 mm.

RESULTS OF FLAT JET NOZZLE

Flat jet nozzles are often used when particularly even cooling has to be achieved. For this purpose, small nozzle angle is investigated. The influence of the nozzle angle on the maximum heat flux is shown in Figure 7.

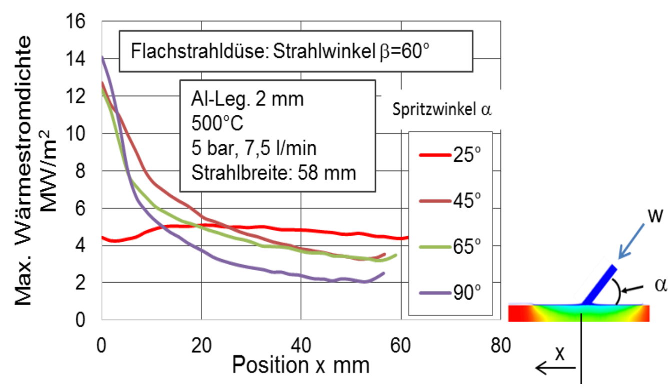

Figure 7 Influence of nozzle angle on maximum heat flux

At a spray angle of 25 °, an approximately constant heat flux is achieved. Spray angles of 45 ° to 90 ° produce large heat flux in the centre region surrounding the impingement line and then decrease with increasing radius exponentially until a constant value is attained. The high heat flux for angles of 45 ° to 90 ° in the vicinity of the impact line up to ca. x = 10 mm are an effect of the jet impingement. From x = 30 mm on, the tendency is reversed. The impact of the direct jet momentum is minimised, meanwhile the accumulated water amount is then dominant. The liquid amount in the x-direction is greater at the spray angle 25 ° and therefore produces a higher heat flux there than at 90 °. This is due to the fact that at 90 °, the water volume is divided into two equal flow streams, which spread in opposite direction on the metal surface. The illustrated phenomenon of the influence of the nozzle angle also plays a role in secondary cooling in the continuous casting.

RESULTS OF COMPARISONS BETWEEN FULL JET AND SRPAY NOZZLES

Figure 8 shows the cooling profiles of an aluminum plate by using spray and full jet nozzle with the same volume flow rate. At first glance, it can be seen that a faster cooling rate is achieved with the full jet nozzle. The cooling curves for both nozzles are fundamentally different from each other. The spray cooling initially begins with a substantially lower cooling gradient until temperature of ca. 280 °C is reached, below which a higher cooling gradient can be observed. This point marks the transition from film boiling to transition boiling and is shown on the quenching side by the sudden wetting of the surface. The temperature at which the wetting takes place is designated rewetting temperature. It is a typical parameter to characterize high-temperature boiling phenomenon. By contrast, completely different pattern is shown for full jet nozzle. In the vicinity of the impact point of the jet, a strong cooling rate can be observed, which is 10 times higher than that of the spray nozzle.

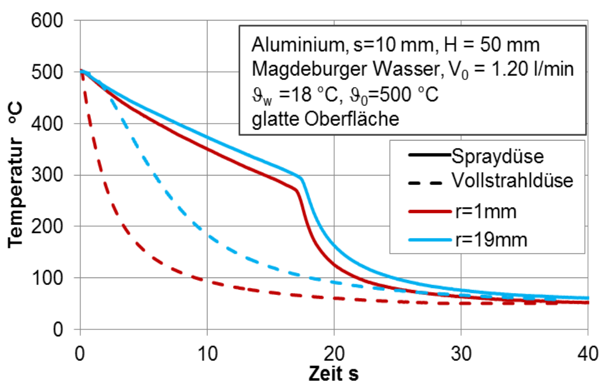

Figure 8 Comparison of full jet and spray nozzle

Considering spray nozzle, from 500 °C to ca. 300 ° C the curve can be assumed as a linear function, which is then followed by a hyperbola-like function with smaller cooling rate. However, in the vicinity surrounding the impact point of the full jet, rewetting temperature cannot be detected due to the limitation of the frequency of the infrared camera. However, if a point is located at a larger radius away from the impingement point, e.g. at r = 19 mm, a s-shaped curve is observed by a closer inspection. The cooling rate increases with the cooling time from almost zero to a maximum value, which is about 300 °C. This corresponds to the DNB temperature. Thereafter, the cooling rate drops until a steady state is reached. The rewetting front separates the wetted from the non-wetted area, at which the rewetting temperature has to be determined. It is defined as the temperature at which the first derivative of the cooling rate reaches a minimum. This is about 400 °C at an initial temperature of 500 °C for full jet nozzle and therefore higher than that of the spray nozzle at about 280 °C.

CONCLUSION

In the centre area of the investigated full jet and flat jet nozzles, an extremely strong cooling rate due to immediate rewetting is attained. Terms such as rewetting and Leidenfrost temperature are not applicable here. Away from the centre area a wetting front with a decreasing velocity spreads outwards. At the wetting front, heat transfer is mainly transition and nucleate boiling. The temperature on the metal surface at which this transition takes place is referred as the rewetting temperature. The main influence on the rewetting temperature is the initial temperature of the metal. The metal type, diameter and velocity of the full jet have a small influence on the rewetting temperature. The DNB temperatures fluctuate around 300 °C and tend to rise with the increased initial temperature. At a nozzle angle smaller than 25 °, an approximately constant heat flux along the liquid stream is established for a flat jet nozzle. The metal initially is cooled slowly without wetting the surface in the area covered by the spray, when the rewetting temperature is reached, a larger cooling rate is obtained.

REFERENCES

[1] J. Hammad, Y. Mitsutake, M. Monde, 2004: Movement of maximum heat flux and wetting front during quenching of hot cylindrical block. International journal of thermal sciences. 43 (2004) 743-752.

[2] P. L. Woodfield, A. K. Mozumder, M. Monde, 2009: On the size of the boiling region in jet impingement quenching. International Journal of Heat and Mass transfer. 52 (2009) 460-465.

[3] F. Puschmann: Experimentelle Untersuchung der Spraykühlung zur Qualitätsverbesserung durch definierte Einstellung des Wärmeübergangs. Dissertation 2003, Otto-von-Guericke-Universität Magdeburg.

[4] M. Attalla: Experimental investigation of heat transfer characteristics from arrays of free impinging circular jets and hole channels. Dissertation 2005, Otto-von-Guericke-Universität Magdeburg.

[5] K. Abdalrahman: Influence of water quality and kind of metal in secondary cooling zone of casting process. Dissertation 2012, Otto-von-Guericke-Universität Magdeburg.

[6] Sabariman: Heat transfer analysis in metal quenching with sprays and jets. Dissertation 2015, Otto-von-Guericke-Universität Magdeburg.

[7] M. Gradeck, J. A. Quattara, B. Remy, D. Maillet, 2012: Solution of an inverse problem in the hankel space – infrared thermography applied to estimation of a transient cooling flux. Experimental thermal fluid science 36 (2012) 56-64.

[8] A. Laberque, M. Gradeck, F. Lemine, 2015: Comparative study of the cooling of a hot temperature surface using sprays and liquid jets. International journal of heat and mass transfer. 81(2015) 889-900.dasdsdadsaddedaddadadaddadasda

[9] A. Laberque, M. Gradeck, F. Lemine, 2016: Experimental investigation of spray impingement hydrodynamic on a hot surface at high flow rates using phase Doppler analysis and infrared thermograpy. International journal of heat and mass transfer. 100 (2016) 65-78.