CHEMICAL ENGINEERING TRANSACTIONS
VOL. 88, 2021
A publication of AIDIC
The Italian Association
of Chemical Engineering
Online at www.cetjournal.it
Guest Editors: Petar S. Varbanov, Yee Van Fan, Jiří J. Klemeš

ISBN 978-88-95608-86-0; **ISSN** 2283-9216
DOI: 10.3303/CET2188041

Heat Transfer and Water Consumption of Water Spray Cooling of High-Temperature Surfaces: A Review on Empirical Correlations

Lubomír Klimeš[a,*], Pavel Charvát[b], Josef Štětina[b]

[a] Sustainable Process Integration Laboratory – SPIL, NETME Centre, Brno University of Technology, Technická 2896/2, 61669 Brno, Czech Republic
[b] Energy Institute, Faculty of Mechanical Engineering, Brno University of Technology, Technická 2896/2, 61669 Brno, Czech Republic
klimes@fme.vutbr.cz

Water spray cooling by spray nozzles is used in many technological and engineering applications, ranging from cooling of electronic devices to metal processing in steelmaking. In the latter case, the setup of water spray cooling have a significant influence on the quality of the produced steel as well as on the consumption of water for cooling, and thus on water footprint. The casting processes are often controlled by means of computer models. In such case, spray cooling is characterised in the form of boundary conditions. There are many empirical correlations available in the literature. However, there is a lack of a study, which would compare them to each other from the viewpoint of heat withdrawal and the water consumption. The present paper aims to fill this gap and the results demonstrate that an appropriate correlation for a considered case has to be selected thoroughly, taking into account various aspects. The results show that the correlations differ about 20-times in terms of heat withdrawal and more than 400-times in terms of the water consumption.

1. Introduction

In many processes, forced cooling is applied to cool or maintain the system in a desired temperature range or to follow a certain temperature-dependent pattern (history). A great portion of such cases employs spray cooling by means of spraying nozzles with a suitable coolant. The nozzle provides atomisation of the cooling medium, meaning that a spray consisting of a large number of small droplets is created. The spray and its droplets hit the surface, and allows for convective heat transfer, often accompanied by the evaporation. Water is a typical coolant, though other liquids possessing suitable characteristics are also used.

The use of spray cooling is rather wide. One important group of the applications is closely related to a recent significant development and use of systems, which include electronic components. Together with an increasing requirement for miniaturisation of such systems (including their dimensions as well as their weight), spray cooling is one of the frequently adopted approaches for cooling of these systems. Another important area of spray cooling including high-temperature surfaces is steelmaking and hot rolling. Water spray cooling is currently one of the main approaches for controlled heat withdrawal in continuous steel casting, significantly affecting the final quality of steel and the occurrence of quality issues, such as cracks or internal defects. A similar situation also occurs in hot rolling of steel plates.

The importance of spray cooling in continuous steel casting and metal production was addressed by many investigators. For example, Yu et al. (2019) investigated dynamic optimisation of water-spray cooling system in continuous steel casting, employing a computer heat transfer model of the process for the determination of optimal water flow rates through the cooling nozzles. They showed that their control algorithm allowed for the stabilisation of the temperature distribution. Wang et al. (2019) applied a model predictive control for spraying system in continuous steel casting by means of a fast computer model and they reported that the algorithm showed a good computational and control performance. Petrus et al. (2020) presented a model for simulations of dynamic thermal behaviour of continuous steel casting, including thermal shrinkage prediction. A case study was performed and the authors reported that the PI control of spray cooling had a much better performance

Paper Received: 26 April 2021; Revised: 12 July 2021; Accepted: 8 September 2021
Please cite this article as: Klimeš L., Charvát P., Štětina J., 2021, Heat Transfer and Water Consumption of Water Spray Cooling of High-Temperature Surfaces: A Review on Empirical Correlations, Chemical Engineering Transactions, 88, 247-252 DOI:10.3303/CET2188041

than a simple spray-table control. Chen et al. (2020) investigated spray cooling of high-temperature surfaces. They analysed factors influencing the convective heat transfer coefficient (HTC) of the spray and emphasised that a great part of the simulation and optimisation studies employ empirical correlations for the characterisation of the heat withdrawal by spray nozzles.

As mentioned, computer models for continuous steel casting in many studies adopt empirical correlations for spray cooling and for the estimation of the HTC. This is also the case of the first three works mentioned in the previous paragraph. However, even though some correlations were adopted in these and also other works on similar topics, no or only very limited information justifying or explaining the selection and behaviour of the particular correlation is provided. The present paper focuses on filling this research gap and its main goal is a basic qualitative comparison of the correlations collected in the literature. Moreover, apart from the heat withdrawal viewpoint, the present study also focuses on the environmental viewpoint and addresses the correlations from the water consumption viewpoint, which was rarely addressed in the previous works.

2. Empirical correlations for characterisation of water spray cooling

Experimental investigation of spray cooling is expensive and time-consuming. Moreover, a number of datasets under various operational conditions are needed for a precise estimation of the HTC. That is the reason why most researches tend to adopt empirical correlations for the HTC rather than undergo experimental investigation. Many empirical correlations for the estimation of the HTC are available in the literature. However, they differ in their complexity, in the number of involved parameters and their range, and, of course, in the values of the predicted HTC. The most influencing parameters include the water spray density and the surface and water temperature. However, other parameters, such as the surface conditions, the distance between the nozzle exit and the surface, and the relative velocity of the nozzle with respect to the surface can also influence spray cooling, though these parameters have rather minor effects.

The great work in terms of the empirical correlations for the HTC and high-temperature surfaces was done in 1970's by Nozaki and his team. Nozaki et al. (1976) reported the correlation for the HTC

$$\mathrm{HTC} = f(\dot{W}, T_w, \alpha) = 1570\,\dot{W}^{0.55}(1 - 0.0075\,T_w)/\alpha \tag{1}$$

and it has been widely adopted by many investigators. They correlated the HTC with the water spray density distribution $\dot{W}$ and the water temperature T_w. The main drawback is the parameter α involved in the correlation, which is a caster-dependent parameter with no exact determination. The parameter α can therefore be considered as a fitting parameter, which can be optimised and determined to achieve the agreement between the simulation and some suitable experimental data (frequently the surface temperature, which is measured by a pyrometer - an infrared thermometer - in several locations along the cast strand in steelworks). Zhang et al. (2009) modified the Nozaki's correlation, determined a particular value of the parameter α, and reported the correlation for the HTC as

$$\mathrm{HTC} = f(\dot{W}, T_w) = 5849\,\dot{W}^{0.451}(1 - 0.0075 T_w) \tag{2}$$

Mitsutsuka and Fukuda (1983) reported another correlation for the HTC, which is a function of the water spray density $\dot{W}$ and the surface temperature T_s, reading (Totten et al., 1993)

$$\mathrm{HTC} = f(\dot{W}, T_s) = \frac{2.9 \cdot 10^9\,\dot{W}^{0.616}}{T_s^{\,2.445}} \tag{3}$$

Hodgson et al. (1993) proposed a rather complex formula for the HTC, taking into account the water spray density $\dot{W}$ and the surface temperature T_s, resulting in

$$\mathrm{HTC} = f(\dot{W}, T_s) = 3.15 \cdot 10^9\,\dot{W}^{0.616}\left[1 - \frac{1}{\exp\{0.025 T_s - 6.25\} + 1}\right]\left[700 + \frac{T_s - 700}{\exp\{0.1 T_s - 70\} + 1}\right]^{-2.455} \tag{4}$$

Similarly, a complex correlation, which takes into account the water spray density $\dot{W}$ and both the surface and water temperature in terms of their difference as $\Delta T = T_s - T_w$, was proposed by Wendelstorf et al. (2008) and it reads

$$\mathrm{HTC} = f(\dot{W}, \Delta T) = 190 + \left[140\,\dot{W}\left(1 - \frac{\dot{W} \cdot \Delta T}{72000}\right) + 3.26\,\Delta T^2\left(1 - \tanh\frac{\Delta T}{128}\right)\right] \cdot \tanh\frac{\dot{\mathrm{W}}}{8} \tag{5}$$

On contrary, Ramstorfer et al. (2009) used a simple correlation, depending only on the water spray density $\dot{W}$

$$\mathrm{HTC} = f(\dot{W}) = 191.1\,\dot{W}^{0.55} \tag{6}$$

As the above correlations illustrate, various relationships with different complexity and taking into account various parameters exist for the estimation of the HTC for water-spray cooling nozzles. In the next sections, an analysis of the correlations is presented and they are assessed from two viewpoints: heat transfer and water consumption. Obviously, these viewpoints can hardly be addressed directly from the mathematical formulation of the correlations, as the influencing parameters are involved in complex mathematical expressions, including power, exponential, or even goniometric functions.

3. Influencing parameters in correlations for water spray cooling

The correlations considered in this study involve four parameters (inputs): the water spray density $\dot{W}$, the surface temperature T_s of the cooled surface, the temperature T_w of water used in the spray, and the caster-dependent parameter α. The temperatures are rather straightforward; a reasonable temperature range for T_s is from about 400 °C (in hot rolling) to about 1,000 °C (in continuous steel casting) while an applicable range for T_w is from 5 °C (in winter) to 30 °C (in summer), depending also on the water resource.

As for the water spray density of cooling nozzles, a current trend is to employ a larger number of rather smaller nozzles (in terms of the total water flow rate) arranged in independent loops, which allow for a better and more precise control of spray cooling. A typical water flow rate $\dot{Q}$ therefore ranges between about 2 L/min to 10 L/min. Since the water spray density $\dot{W}$ in L/(m^{2}s) involved in the correlations characterises the spatial distribution of the water spray, a suitable functional dependence for $\dot{W}$ is needed. In case of full-cone nozzles, which produce the cone-shape spray, the following bell-shape function having the shape similar to the probability density function of the normal distribution (often referred to as the Gaussian-shape function) is a reasonable assumption

$$\dot{W} = f\left(A, x, y, B_x, B_y\right) = A\left(\exp\left\{\frac{-x^2}{2B_x^2}\right\} + \exp\left\{\frac{-y^2}{2B_y^2}\right\}\right) \tag{7}$$

where A, B_x, B_y are constants characterising the shape of the function (explained in detail below) and x, y are spatial coordinates. Let us consider the full-cone nozzle, which is positioned $H = 100\ \mathrm{mm}$ from the cooled surface. The cone angle θ differs with the particular type and producer of the nozzle but in general it ranges between 45° and 90°. Considering $\theta = 65°$ as a representative value, the diameter of the circular surface wetted by the nozzle is 2*H* tan(*θ*/2) ~ 130 mm. The constants B_x, B_y are set to values, which guarantee the considered diameter of the wetted circular surface. On the other hand, the constant A requires a more careful treatment as its value must be chosen so that

$$\iint_{x,y=-\infty}^{x,y=\infty} \dot{W}\ \mathrm{d}x\ \mathrm{d}y = \dot{Q} \tag{8}$$

meaning that the water flux density distribution corresponds to the considered water flow rate through the nozzle. Figure 1 shows the water spray density modelled by Eq(7), which corresponds to the water flow rate of 6 L/min determined according to Eq(8) with the diameter of the wetted circular surface of about 130 mm. The constants of the bell-shaped function was set to $A = 25.5$ and $B_x = B_y = 0.025$.

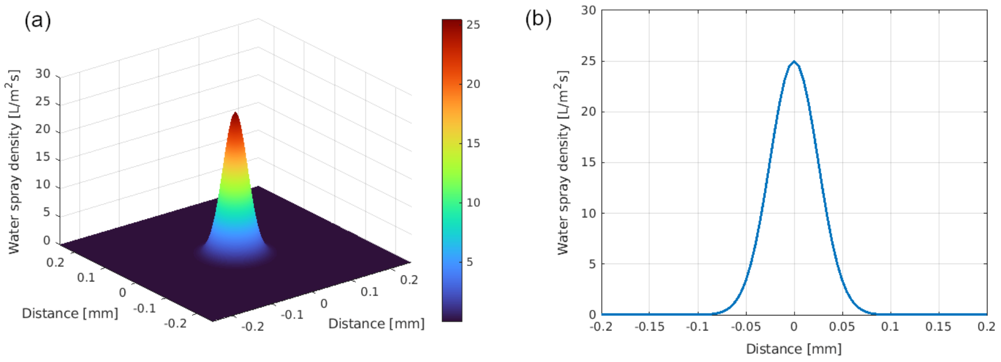

Figure 1: Water spray density distribution of a cooling nozzle with the total water flow rate of 6 L/min: (a) an overall distribution over the surface, (b) a line distribution under the exit of the nozzle

Figure 1a demonstrates the overall distribution of the water spray density $\dot{W}$ on the 2D cooled surface while the plot (b) on the right shows a line projection (cross-section) of $\dot{W}$ in the plane perpendicular to the cooled surface and running through the exit of the nozzle. The water spray density shown in Figure 1 is considered as a representative water spray density distribution in the following analysis of the heat transfer and water consumption analysis.

4. Heat transfer assessment of empirical correlations for water spray cooling

The water spray density distribution corresponding to the total water flow rate of 6 L/min shown in Figure 1 was applied to the empirical correlations for the HTC presented in Eq(1)-(6), considering the surface temperature of 900 °C and the water temperature of 20 °C. Since the research works employing the correlation given in Eq(1) do not provide sufficient information about the particular value used for the fitting parameter α, its value was set to 1 for simplicity.

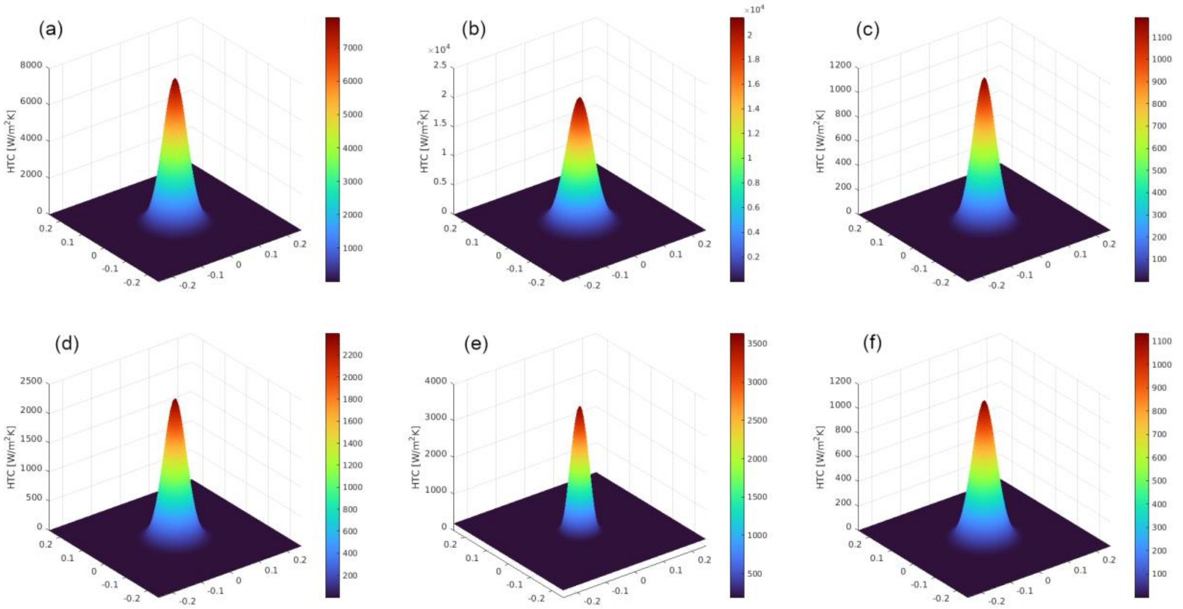

Figure 2: Estimations of the heat transfer coefficient gained with the use of empirical correlations: (a) correlation in Eq(1) by Nozaki et al. (1976), (b) correlation in Eq(2) by Zhang et al. (2009), (c) correlation in Eq(3) by Mitsutsuka (1983), (d) correlation in Eq(4) by Hodgson et al. (1993), (e) correlation in Eq(5) by Wendelstorf et al. (2008), (f) correlation in Eq(6) by Ramstorfer et al. (2009)

As can be seen in Figure 2, the peak values of the HTC differ quite significantly from one correlation to another one. That is the reason why each subplot in Figure 2 has its own range for the HTC (the range of the *z*-axis), as making it uniform for all cases would significantly decrease legibility of the individual plots. Hence, each case in Figure 2 requires consideration of the corresponding colour map. For the considered setup, the correlations in Eq(3) and Eq(6) shown as cases (c) and (f) in Figure 2 indicate a similar behaviour to each other with the peak value of the HTC of about 1,100 W/m^{2}K. These values are the lowest peak values in the considered set of correlations. Such rather low values of the HTC are typical for the film boiling regime and are in agreement e.g. with data presented by Vorster et al. (2009). In case of the film boiling regime, the surface temperature is higher than the so-called Leidenfrost temperature and a vapour layer created on the cooled surface prevents the water spray from the impingement of the water droplets to the surface and from the intensive heat withdrawal. On the other hand, the cases (a) and (b) in Figure 2, which correspond to the correlations in Eq(1) and Eq(2), lead to high peak values of the HTC (,8000 W/m^{2}K and 21,000 W/m^{2}K), which are the highest peak values of the HTC in the set of considered correlations. Such high values are typical for rather low surface temperatures below the Leidenfrost temperature in the nucleate boiling regime, which occurs near the temperature, in which the heat flux attains its maximum (the so-called critical heat flux). The remaining two cases (d) and (e), which correspond to the correlations in Eq(4) and Eq(5), can be considered, from the viewpoint of the peak HTC (2,200 W/m^{2}K and 3,500 W/m^{2}K), somewhere between the discussed minimum and maximum values. However, it needs to be emphasised that each correlation is proposed and/or valid in a certain range of input parameters and other conditions. In case they are (more or less) out of the range, the accuracy of the prediction decreases accordingly. For example, the correlation in Eq(4) was proposed for the surface temperature up to 800 °C while the correlation in Eq(6) was derived from experimental data with the surface temperatures of 950-1250 °C. The present analysis adopted the surface temperature of 900 °C, which can be considered as a temperature, which reasonably violates these ranges, still preserving a certain level of accuracy. However, for a more accurate analysis, several surface temperatures strictly within the specified ranges should be analysed.

It is clear from the above analysis that even though the peak values of the HTC are reasonable for certain (but distinct) operational conditions, they differ quite significantly one to each other. Since the peak value for one correlation (Eq(2)) is about twenty-times higher than some other correlations (Eq(3) and Eq(6)), the selection of the correlation requires attention, and its particular use should be analysed in detail, justified and also validated. However, as mentioned above, in many research works these details and information are limited, or even completely missing.

5. Water consumption assessment of empirical correlations for water-spray cooling

Recently, many research works were reported on the assessment of water consumption in the steel industry. For example, Gao et al. (2020) created a model for the prediction and analysis of the water and energy saving in the steelmaking process. In their case study for China, they considered various scenarios and reported that there is a potential to decrease the consumption of energy and water by 2025 to about 15 GJ/t and 54-59 m^3/t. Research works addressing the water consumption and its minimisation in continuous steel casting were also reported. For example, Wang et al. (2013) presented a study, in which a computer model was applied in optimisation of the secondary cooling system and the authors reported that the optimised configuration of the cooling setup and water flow rates allowed for about a 10% decrease of the water consumption. Obviously, in case the computer models employing the empirical correlations for the HTC are used to assess the water consumption in continuous steel casting, the consideration of a particular correlation for the HTC has a direct influence to the evaluation of the water consumption and potentials for its minimisation.

In this section, the above analysed empirical correlations are addressed in terms of the water consumption. As indicated in the foregoing section, the estimation of the peak values of the HTC differs quite significantly with the particular correlation used for the prediction. In order to perform a comparison of the correlations from the viewpoint of the water consumption, an identical target peak value of the HTC was set to 2,000 W/m^2K for all the correlations. Simply speaking, the aim was to achieve the identical heat withdrawal performance for all the correlations. Obviously, this requires adjusting the total water flow rate through the nozzle so that the peak value of the HTC reached the target value. This was achieved by optimisation of the parameter A in Eq(7). Table 1 summarises the required water flow rates for the individual correlations.

Table 1: Water flow rates through the nozzle to reach the peak value of the HTC of 2,000 W/m^2K

Correlation	Equation	Case in Figure 1	Water flow rate [L/min]
Nozaki et al. (1976)	Eq(1)	(a)	0.5
Zhang et al. (2009)	Eq(2)	(b)	0.04
Mitsutsuka (1983)	Eq(3)	(c)	13
Hodgson et al. (1993)	Eq(4)	(d)	4.7
Wendelstorf et al. (2008)	Eq(5)	(e)	3.3
Ramstorfer et al. (2009)	Eq(6)	(f)	17.7

As can be seen from Table 1, the water consumption needed for the HTC with the peak value of 2,000 W/m^2K differs and depends significantly on the particular correlation. The minimum value of the water flow rate is 0.04 L/min for the correlation used by Zhang et al. (2009). On the other hand, the correlation utilised by Ramstorfer et al. (2009) requires 17.7 L/min (the maximum value), which is about 440-times higher than in case of the correlation by Zhang et al. (2009). This comparison clearly indicates that the use of a particular correlation significantly influence the estimation of the water consumption - even more than the heat withdrawal performance (the HTC).

6. Conclusions

Empirical correlations for the prediction of the heat transfer coefficient (HTC) of spray cooling nozzles used in continuous steel casting were collected from the available literature and analysed. Even though such correlations are frequently adopted in computer models of continuous steel casting for the optimisation and control of the process, only limited information can be found in the research studies, which would explain and justify the use of the particular correlation. Two viewpoints were addressed: the heat withdrawal performance and the water consumption. In case of the assessment of the heat withdrawal performance, the peak values of the HTC under a constant water flow rate of 6 L/min through the nozzle differed rather significantly with the minimum value of about 1,100 W/m^{2}K and with the maximum value of about 21,000 W/m^{2}K, which makes about a 20-times difference. As for the water consumption viewpoint, the differences were even more pronounced. Considering the target peak value of the HTC of 2,000 W/m^{2}K, one correlation required only 0.04 L/min of water while another correlation required 17.7 L/min to reach the same peak value of the HTC, which makes about a 440-times difference. The results indicate that the selection of the correlation has a significant influence on both the heat withdrawal and water consumption. Therefore, the correlation should be selected with care, analysing its behaviour and taking into account the applicable range of the influencing parameters. The present study adopted some simplifications and imperfections, which the authors plan to further address in the follow-up study, employing experimental investigation of the water density pattern and heat withdrawal. Particularly, the range of conditions, in which the correlations are valid or exhibit a reasonable accuracy (an acceptable error) needs to be addressed, specified and quantified in a greater detail. In case the correlation is used in a computer model of the casting process, the overall behaviour of the model should also be validated with experimental data, e.g. with the surface temperature of the cast steel strand.

Acknowledgements

This work was supported by the project Sustainable Process Integration Laboratory – SPIL, No. CZ.02.1.01/0.0/0.0/15_003/0000456, funded by European Research Development Fund, Czech Republic Operational Programme Research, Development and Education, Priority 1: Strengthening capacity for quality research, and by the Czech Science Foundation under project No. 19-20802S.

References

Chen P., Dai F., Pan L., Guo Y., Ke J., Wu J., Lei Y., Li Y., 2020, Secondary cooling in continuous casting and Leidenfrost temperature effects, Applied Thermal Engineering, 181, 116011.

Gao C., Na H., Song K., Tian F., Strawa N., Du T., 2020, Technologies-based potential analysis on saving energy and water of China’s iron and steel industry, Science of the Total Environment, 699, 134225.

Hodgson P.D., Browne K.M., Collinson D.C., Pham T.T., Gibbs R.K, 1993, A mathematical model to simulate the termomechanical processing of steel, Chapter In: Hodgson P.D., Quenching and carburising: Proceedings of 3rd International Seminar of International Federation for Heat Treatment and Surface Engineering, Alden Press, Osney Mead, Oxford, UK, 127-138.

Mitsutsuka M., Fukuda K., 1983, Cooling characteristics and heat transfer coefficients during water-spray cooling of hot steel plate, Tetsu-to-Hagane, 69, 262-267.

Nozaki T., Matsuno J., Murata K, Ooi H., Kodama M., 1976, Secondary cooling pattern for the prevention of surface cracks of continuous casting slab, Tetsu-to-Hagane, 62, 1503-1512.

Petrus B., Chen Z., Bentsman J., Thomas B.G., 2020, Investigation dynamic thermal behaviour of continuous casting of steel with CONOFFLINE, Metallurgical and Materials Transactions B, 51, 2917-2934.

Ramstorfer F., Roland J., Chimani C., Mörwald K, 2009, Modelling of air-mist spray cooling heat transfer for continuous slab casting, International Journal of Cast Metals Research, 22, 39-42.

Totten G.E., Bates C.E., Clinton N.A., 1993, Handbook of quenchants and quenching technology, ASM International, Novelty, OH, USA.

Vorster W.J.J., Schwindt S.A., Schupp, J., Korsunsky A.M., 2009, Analysis of the spray field development on a vertical surface during water spray-quenching using a flat spray nozzle, Applied Thermal Engineering, 29, 1406-1416.

Wang Y., Luo X., Zhang F., Wang S., 2019, GPU-based model predictive control for continuous casting spray cooling control system using particle swarm optimization, Control Engineering Practice, 84, 349-364.

Wang Z., Yao M., Zhang X., Wang X., 2013, Optimisation control for solidification process of secondary cooling in continuous casting steel, Applied Mechanics and Materials, 263-266, 822-827.

Wendelstorf J., Spitzer K.H., Wendelstorf R., 2008, Spray water cooling heat transfer at high temperatures and liquid mass fluxes. International Journal of Heat and Mass Transfer, 51, 4902-4910.

Yu Y., Luo X., Zhang H., Zhang Q., 2019, Dynamic optimization method of secondary cooling water quantity in continuous casting based on three-dimensional transient nonlinear convective heat transfer equation, Applied Thermal Engineering, 160, 113988.

Zhang X.Z., Jiang Z.Y., Tieu A.K., Thu H.T., Tian Z.W., 2009, Analysis of surface temperature and thermal stress field of slab continuous casting, Advanced Materials Research, 76-78, 554-559.