Numerical method for modelling spray quenching of cylindrical forgings

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Nowadays, in steel industries, spray quenching has been used as a cooling method for the microstructure optimization after a forging process. In comparison with other cooling systems, there are many process parameters involved in spray quenching, which make it versatile, effective and able to adapt the quenching upon different cross sections of heavy parts.
Simulation can represent a useful tool in properly designing the spray process for a specific forging and its reliability depends on the proper definition of input data, in particular of the heat transfer coefficient between the water and the part.
Volumetric spray flux has been proposed as one of the preeminent factors on determining the heat transfer coefficient during spray quenching. In industrial processes, the volumetric spray flux is affected by the overlap of sprays on the forging surface due to the use of multi-nozzles systems.
The present paper is aimed at developing a method able to take into account, by using a defined amplification factor, the effect of overlapping of sprays on the heat transfer coefficient to be applied in simulation of quenching processes.

KEYWORDS: Spray Quenching, Heat Transfer Coefficient, Overlapping, Volumetric Flux

NOMENCLATURE					
a, b, c, d	Points defined in fig.5	S	Distance between vertical upright (Fig.1)		
c_p	Specific heat of water at constant pressure	T	Temperature		
D	Diameter of part in each cross section	ΔT	$T_s - T_f$	T_f	Water Temperature
d_o	Nozzle orifice diameter	ΔT_{sub}	$T_{sat} - T_f$	T_s	Surface Temperature
d_{32}	Sauter mean diameter	ΔT_{MIN}	$T_{MIN} - T_{sat}$	T_{sat}	Saturation Temperature
h	Heat Transfer Coefficient	ΔT_{CHF}	$T_{CHF} - T_{sat}$		
H	Distance from orifice to hot surface	U_m	Mean droplet velocity		
H^*	Distance Ratio, $H^* = H/D$				
h_{fg}	Latent heat of vaporization	**Subscripts**		**Greek symbols**	
L	Distance aligned nozzles (Fig.1)	*CHF*	Critical heat flux	α	Amplification factor
N	Number of adjacent nozzles	*f & g*	Liquid and Vapour	β	Overlapping angle (Fig.4)
n	Radius of spray impact area	*MIN*	Leidenfrost point	μ	Viscosity
Q	Volumetric flow rate per nozzle	*s*	Surface	ρ	Density
q''	Heat flux	*sub*	Sub-cooling	σ	Surface tension
$\overline{Q''}$	Mean volumetric spray flux	*sat*	Saturation	θ	Spray cone angle

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INTRODUCTION

Quenching is usually performed in order to improve the mechanical properties of steel parts as a consequence of the microstructural changes taking place when the steel is cooled down quickly from high temperatures. Difficulties in obtaining the proper performance can arise when treating large components because of the inhomogeneous temperature distribution along the sections and in the different cross-sections, which can be able to induce unwanted residual stresses [1]. Hence, there is a demand to implement a controllable system able to quench each cross-section as uniformly as the others to achieve the needed metallurgical properties everywhere in the part. In relation to this aim, nowadays, spray quenching has been utilized as a cooling procedure for the microstructure optimization afterwards a forging process of large parts [2].

In spray cooling, the quenchant, usually water, is sprayed via a set of orifices onto the hot surface of the metallic part. There is a set of process parameters which allows in principle to adjust the cooling process to the metallurgical demands, like applying different volumetric water fluxes according to the different cross-sections, or using a timed cooling in the various areas of the part, etc. Unfortunately there is only small knowledge available to regulate and optimize the process and, consequently, it's still a matter of trial and error. Thus, the high cost of heavy-forged components with large dimensions forces to develop simulation methods that provide comprehensive and reliable information about the thermal behaviour during the spray quenching [3]. These methods allow to make a computer supported design of the process, minimizing the expensive experimental work, and to predict the final quality of the products.

However, the reliability of the simulation and modelling of the process is based on the proper definition of input parameters, in particular of the heat transfer coefficient between the water and the part in the impingement area. Therefore, simulation model should be validated in order to guarantee the correct prediction of the temperature distribution in the component [4]. Validation is obtained by comparing calculations and experimental tests that, in case of heavy forgings, cannot be performed on small laboratory samples as they are not fully representative of the behaviour of large sections during heat treatment.

There are some theoretical methods to determine the local and overall heat transfer coefficient when a hot part is exposed to the flow of a water spray. This research models the spray quenching of a heavy forging based on the methods proposed by Mudawar and Valentine [5].

The knowledge of the water distribution and the consequent local heat fluxes allows to design a cooling system able to guarantee the proper cooling rate in the different cross sections of heavy forged parts, in order to achieve the desired metallurgical properties everywhere.

A controllable spray quenching process can adjust the heat transfer according to the different diameters by modifying the volumetric spray flux and the active time duration of the spray. To do that, a set of several nozzles are usually arranged in longitudinal rows (also called uprights) placed at a certain distance around the work-piece. In this kind of configurations, overlapping of spray droplets released by adjacent spray nozzles results in an increase of volumetric flux which causes an increase in heat flux as well. Hence, it is important to understand not only the spray distribution and heat flux for a single spray nozzle but also for a multi-spray nozzle arrangement.

Aim of the current research is to develop a method for numerical modelling of the spray quenching. In particular, this study is intended for gathering the different effective parameters in the simulation of spray quenching over the heavy forgings and for determining the heat transfer coefficient when overlapping nozzles are acting on the forging surface.

MODELLING OF SPRAY QUENCHING FOR A SINGLE SPRAY NOZZLE

In order to define the heat transfer coefficient between the water and the part, when a multi-spray nozzles system is used, a cylindrical forging is taken as reference geometry. In particular, to assess the influence of nozzle-part distance on spray impact area, a forged shaft with different diameters is considered. The request for producing a uniform water distribution over the surface can be complied by the use of a spray coverage with a set of several nozzles. For the current study, the spray nozzles are aligned over vertical movable columns that are called "Uprights" placed diametrically around the forged part. Each upright is vertically composed by 2 parallel columns with a fixed distance (S); in addition, the spray nozzles are aligned along the vertical uprights at same distance (L) (Fig. 1).

H* is introduced as a dimensionless number, named "Distance Ratio", defined as the ratio between the distance orifice-nozzle (H) and the diameter of the part in each cross section (D); that is given as:

$$H^* = \frac{H}{D} \tag{1}$$

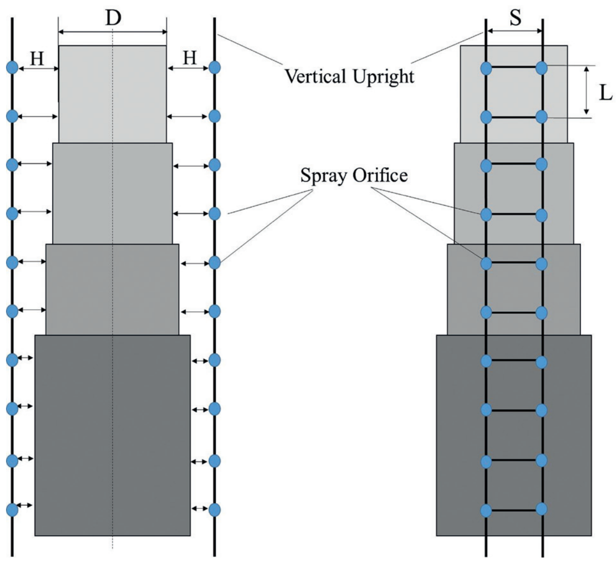

Fig. 1 - Spray quenching system along a cylindrical metal part with increasing diameters

The water distribution on the surface has been proposed as the preeminent factor affecting heat transfer coefficient and the volumetric spray flux has been pointed out as a parameter indicating the distribution of water flux on the surface per unit area [6]. The model used to determine the volumetric spray flux is based on the method developed by Mascarenhas and Mudawar [7] for a single full cone spray impinging a cylindrical surface, which comes from the methods previously proposed for a flat surface [8].

Determination of Volumetric Spray Flux

The volumetric flux changes locally from a maximum at a point on the centre line of the nozzle to the external edge of the spray impact area [7]. In the current model, it is assumed that the spray water is distributed uniformly over the whole spray impact area with a "mean volumetric spray flux" ($\overline{Q''}$). Additionally, although spray impact area should have a shape of an ellipse, in the present study it is assumed as circular with the radius of "n" as shown in Figure 2.

Figure 2 illustrates a single spray impingement area over a cylindrical unit cell, in which the spray axes (XZ) are set at the centre of spray impact area in front of spray orifice nozzle.

Because it exists a correlation between the geometry of the forging and the spray impact area, it is important to point out the effect of the change in the system configuration (i.e. varying the diameter of the part or the distance orifice-surface) on the water distribution over the surface. For example, an increase in distance ratio (H*) leads to an increase in the radius of the spray impact area and, consequently, it can cause the overlapping of the droplets when multi-spray nozzles are used.

The current findings about spray impact area can be generalized to the full cone spray nozzles by Equation (2), which gives the radius of the impact area and, thus, mean volumetric spray flux can be defined by the Equation (3):

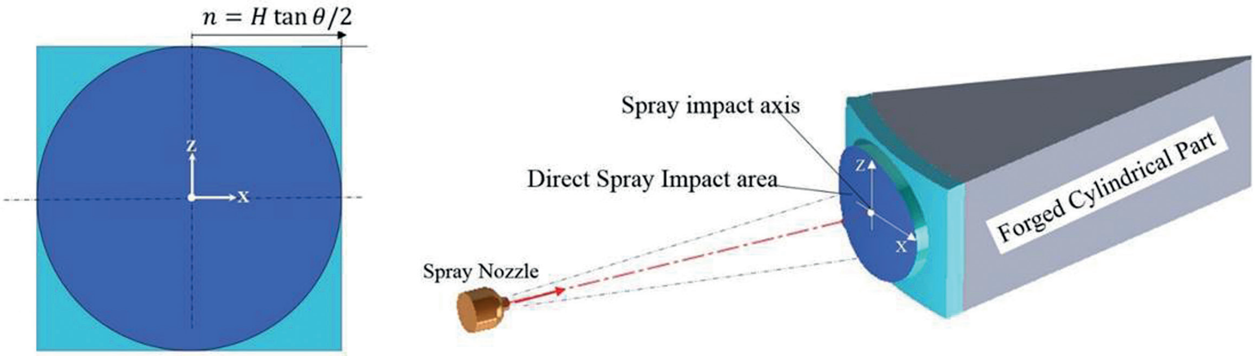

Fig. 2 - Spray impact area over a forged cylindrical part

$$n^* = \frac{n}{D} = H^* \tan\theta/2 \qquad (2)$$

$$\overline{Q''} = \frac{Q}{\pi n^{*2}} D^2 \qquad (3)$$

with θ the cone angle of the nozzle and D the diameter of the part.

Therefore, the volumetric spray water flux can be easily calculated as a function of the area interested by direct spray when the Volumetric flow rate Q is known.

Heat Flux for a single spray nozzle

When the droplets of water contact with the hot surface, according to the surface temperature, evaporation occurs, extracting heat from the part. The resulting heat flux is a function of the temperature difference between the hot surface and the saturation temperature of the water, i.e. the temperature at which water starts to boil for the ambient pressure.

Figure 3 illustrate different regimes of heat flux during spray quenching.

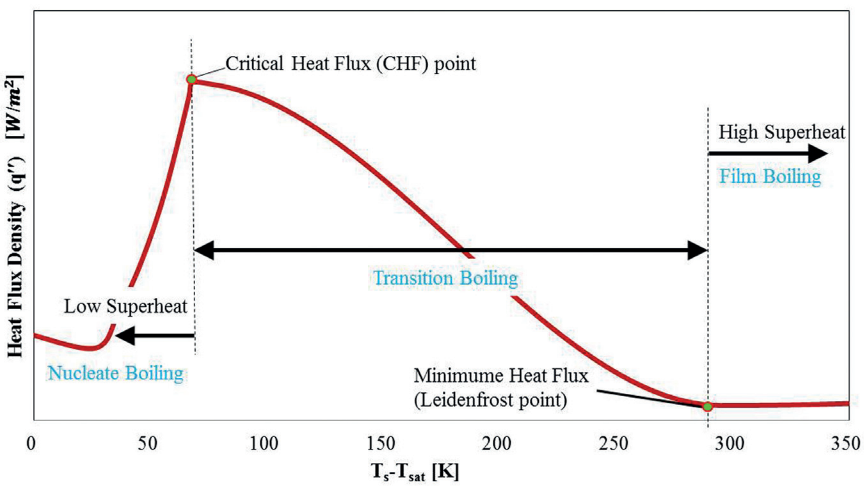

Fig. 3 - Heat flux for a single Spray nozzle

When considering the heat treatment of forgings, it is important to take into account the heat flux in the film boiling region, i.e. at the beginning of the quenching process, when the temperature of the part is high. Leidenfrost point has a strong effect on the spray quenching as it represents, with the lowest level of heat flux, the point where the collapse of the vapour blanket commences. Thus, Leidenfrost is the point where the water starts to soak the hot surface.

During the rapid cooling, after the point of minimum heat flux, a transition occurs which is characterized by a radical increase in heat flux until a critical heat flux (CHF) point is reached. At the CHF point the amount of the bubbles on the hot surface severely decreases. In the transition boiling regime, between Leidenfrost point and CHF, the surface starts to experience wetting. Finally, at the lower superheat, during the nucleate boiling regime, the puncture of droplets and also removal of the vapour bubbles cause that the water droplets are able to touch the hot surface; hence the heat flux level falls sharply [9].

The heat flux can be determined as a function of three spray parameters: mean volumetric flux, mean droplet diameter and mean droplet velocity [7].

The mean volumetric flux can be easily calculated according to equation (3).

The mean droplet velocity, U_m, can be estimated when the orifice diameter and the total volumetric flow rate are known, and it can be considered constant along and away from the spray axis [7].

Concerning the mean droplet diameter, different methods have been proposed to determine it [6] [5]. In spray applications, the mean diameter usually considered is the Sauter diameter (d_{32}) which depends on the nozzle geometry, liquid physical properties and the dynamic parameters of the flow. The definition of this parameter is fundamental to calculate the heat flux.

The spray quenching constitutive equations for film boiling, Leidenfrost temperature and corresponding heat flux and transition heat flux have been developed by Klinzing, et al. [10]:

For film boiling regime:

$$q'' = 63.25\Delta T^{1.691}\overline{Q''}^{0.264}d_{32}^{-0.062} \tag{4}$$

For minimum heat flux and temperature at that Leidenfrost point:

$$\begin{aligned} q''_{MIN} &= 3.324\times 10^{6}\overline{Q''}^{0.544}U_m^{0.324} \\ \Delta T_{MIN} &= 2.049\times 10^{2}\overline{Q''}^{0.066}U_m^{0.138}d_{32}^{-0.035} \end{aligned} \tag{5}$$

For thermal transition boiling regime:

$$\begin{aligned} q'' = q''_{CHF} - \frac{q''_{CHF}-q''_{MIN}}{(\Delta T_{CHF}-\Delta T_{MIN})^3}\big[\Delta T_{CHF}^3 - 3\Delta T_{CHF}^2\Delta T_{MIN} + \\ 6\Delta T_{CHF}\Delta T_{MIN}\Delta T - 3(\Delta T_{CHF}+\Delta T_{MIN})\Delta T^2 + 2\Delta T^3\big] \end{aligned} \tag{6}$$

Mudawar and Valentine [5] pronounced a numerical equation to identify CHF for a cylindrical surface. They measured the critical heat flux at the water spray impact area with respect to the volumetric flux at the outer edge of impact spray area. The proposed numerical equation for the mean value of CHF is shown:

For critical heat flux (CHF):

$$\frac{q''}{\rho_f h_{fg}\overline{Q''}} = 2.3\left(\frac{\rho_f}{\rho_g}\right)^{0.3}\left(\frac{\rho_f\overline{Q''}^2 d_{32}}{\sigma}\right)^{-0.35}\left(1 + 0.0019\frac{\rho_f c_p\,\Delta T_{sub}}{\rho_f h_{fg}}\right) \tag{7}$$

The following equation has been introduced by Rybicki and Mudawar [11] to determine the heat flux for a spray quenching:

For nucleate boiling regime:

$$\frac{q'' d_{32}}{\mu_f h_{fg}} = 0.00479\left\{\frac{c_p\,(T_s - T_f)}{h_{fg}}\right\}^{5.75}\left(\frac{\rho_f}{\rho_g}\right)^{2.5}\left(\frac{\rho_f\overline{Q''}^2 d_{32}}{\sigma}\right)^{0.35} \tag{8}$$

Where $\overline{Q''}$[$m^3\,s^{-1}\,m^{-2}$] is mean volumetric flux, ρ_g and ρ_f [$kg\,m^{-3}$] are density of vapour and water; μ_f [$N\,s\,m^{-2}$] is water viscosity, h_{fg}[$J\,kg^{-1}$] is latent heat of vaporization, c_p [$J\,kg^{-1}K^{-1}$] is specific heat at constant pressure of water and σ [Nm^{-1}] is surface tension. By the implementation of Equation 4, 5, 6, 7 and 8 for different surface temperatures, the spray quenching heat flux (q"[Wm^{-2}]) can be determined by the considering of the variation between surface and spray water temperature (T_s and T_f [K] respectively).

MODELLING OF SPRAY QUENCHING FOR A SET OF SPRAY NOZZLES OVERLAPPED

When impact areas created by adjacent spray nozzles overlap on the surface of the part, the volumetric spray flux increases where the droplets intersect, causing an increase in heat transfer.

To calculate the heat transfer for an arrangement like this the local heat transfer coefficients have to be calculated, taking into account both the areas covered only by one nozzle (light colored areas in Fig.4) and those where the sprays are overlapping (dark colored areas in Fig.4), according to their different volumetric flux densities.

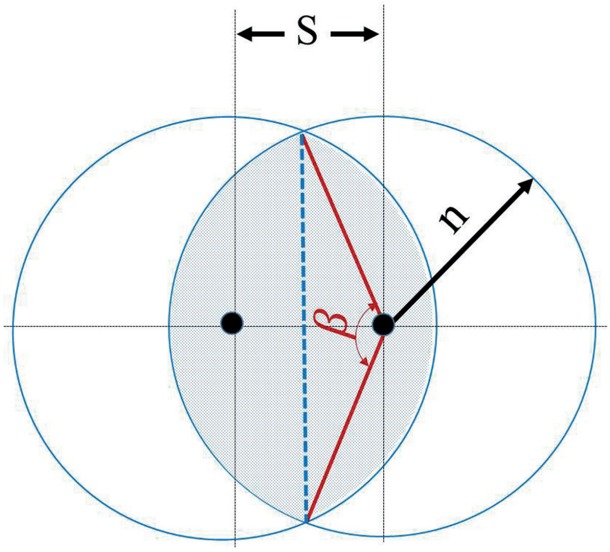

Fig. 4 - The overlapping of adjacent spray impact area

To simplify the calculations, in the present paper it is proposed to apply an amplification factor α which allows to calculate the heat transfer for the whole area with one mean volumetric flux.
The amplification factor α is simply defined by geometrical considerations, in particular as the ratio between the sum of the impingement areas of all nozzles related to the area which is actually covered by all sprays. It follows that α can be equal or larger than one.
For the example of Fig. 4 the amplification factor can be calculated as the ratio between the areas of the two circles and the total real area, considering the overlap.
The mean volumetric flux is then given by the product of α and the flux for a single nozzle, according to eq. (3).
To verify the correctness of this approach, which corresponds in principle with the assumptions of [6], the sum of the heat fluxes for the different areas and the heat flux calculated with the amplification factor have been compared. It shows that the both results differ by not more than 2%, independently of the number of nozzles and the degree of overlapping and independently of the heat transfer regime.
As already mentioned, the amplification factor is a geometrical factor only, depending on the arrangement of the nozzles and of the part. Considering, for example, a linear arrangement of the nozzles, as shown in Fig.4, α is given by:

$$\alpha = 1/\left(1-\left(1-\frac{1}{N}\right)\times\frac{\gamma}{\pi}\right) \tag{9}$$

Where:
N = number of adjacent nozzles,

$\beta = 2\times cos^{-1}\left(\frac{S}{2n}\right)$, expressed in rad

$\gamma = \beta - \sin\beta$
S = distance between two nozzles
n= radius of the impingement.

For large number of nozzles α becomes:

$$\alpha = 1/\left(1-\frac{\gamma}{\pi}\right) \tag{10}$$

Therefore, a new mean volumetric flux can be calculated and considered uniform on the entire area ($\bar{Q}''_{Over}$):

$$\bar{Q}''_{Over} = \alpha\overline{\mathrm{Q}''} \tag{11}$$

The heat flux in the case of multi-spray nozzles quenching can be calculated by equations 4-8 using $\bar{Q}''_{Over}$ instead of $\overline{\mathrm{Q}''}$, while the heat transfer coefficient can be determined by the following equation:

$$HTC = \frac{q''}{\Delta T} \tag{12}$$

where ΔT is the difference between the forging surface and water temperatures.

CASE STUDIED

A shaft characterized by four different diameters was considered as case study (Fig. 1).

Two vertical uprights are fixed at a distance S of 230 mm. They are located at 800 mm from the axis of the shaft, thus, each cross section is characterized by different part-nozzles distance. As a consequence, the volumetric flux and the heat transfer coefficient are different in each sector of the shaft.

Figure 5 illustrates water spray impingement at each distance ratios.

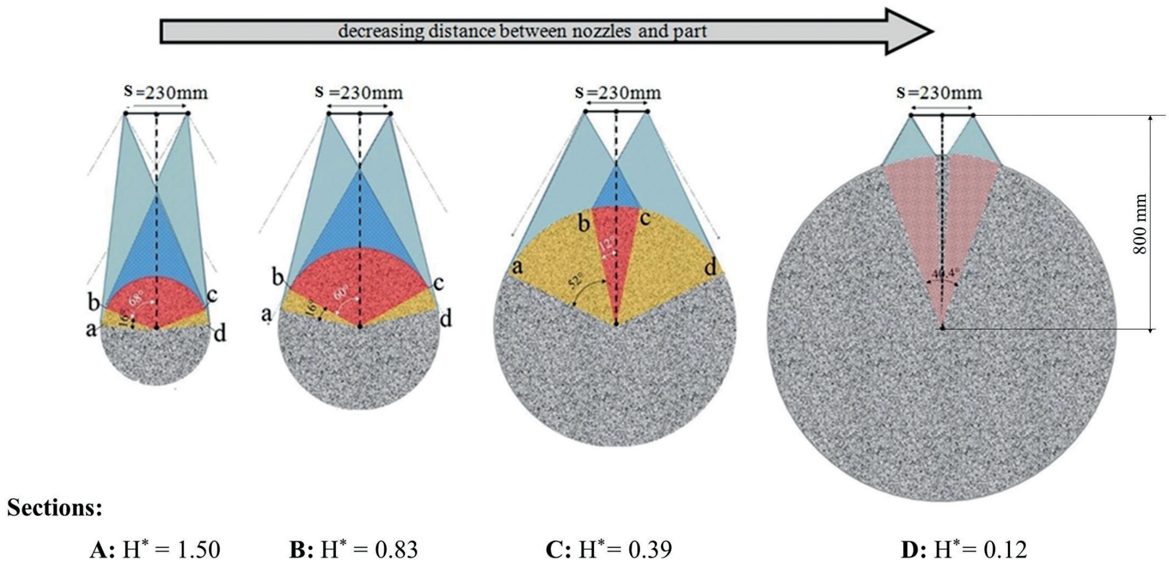

Fig. 5 - Water Spray impingement based on the surface-orifice distance and the diameters of each cross sections

In the section D, characterized by the larger diameter, the small distance between shaft surface and uprights induces the formation of distinct impingement areas that can be treated as a single nozzle spray case for the determination of the heat transfer coefficient. In the other three sections, the smaller is the diameters the larger is the extension of the overlapping area (b-c in Fig.5) compared to the not overlapping one (a-b and c-d in Fig.5). For each section, therefore, a different amplification factor α has to be calculated.

In Table I the used spray system parameters are reported.

Table I Spray nozzles parameters

Full cone Spray angle (θ)	60
Temperature of Water (°C)	20
Nozzle orifice diameter d_o (m)	2.80E-03
Volumetric flow rate per nozzle (m^3/s)	9.74E-05
Pressure across spray nozzle (bar)	3
Mean droplet velocity (m/s)	0.158
Sauter diameter d_{32}(m)	1.15E-04

According to equations 9-10 the mean overlapping volumetric flux can be calculated for each cross section as a function of the amplification factor, as shown in Table II.

As it can be seen, at a fixed distance S between the uprights and distance between nozzles and part axis, the larger is the shaft diameter, i.e. the smaller is the distance nozzles-part, the smaller is the corresponding amplification factor.

Table II Amplification factor and mean overlapping volumetric flux for each section

Section	H*	β [rad]	Amplification (α)	$\overline{Q''}$ $[m^3 s^{-1} m^{-2}]$	Mean Overlapping volumetric spray flux $\overline{Q''}_{Over}$ $[m^3 s^{-1} m^{-2}]$
A	1.50	2.46	1.41	2.58E-04	3.64E-04
B	0.83	2.32	1.34	3.72E-04	4.98E-04
C	0.39	1.93	1.19	7.59E-04	9.03E-04
D	0.12	-	1	4.13E-03	Without overlapping

The mean overlapping volumetric flux is lower at increasing distance nozzle-part, notwithstanding the larger overlapping area, as a consequence of the larger radius of the impingement area (n) when the total volumetric flow rate is constant.
On the base of the amplification factor α the heat transfer coefficient can be calculated. As shown in Fig. 6, expanding the distance orifice-component the heat transfer coefficient decreases. So, notwithstanding the increase of the amplification factor at enlarging the distance, the HTC is reduced because of the lower flux.

More in detail, during the film boiling regime, because of the presence of a vapour blanket on the surface of the hot forging, no big differences in terms of HTC can be detected varying the distance ratio H*. With increasing volumetric spray flux by reducing the distance, the Leidenfrost point can be reached slightly sooner. Thus, HTC can switch from low film boiling regime to high transition boiling regime at slightly higher surface temperature. Additionally, the level of CHF increases at lower distance ratio, increasing the maximum of the heat transfer coefficient.

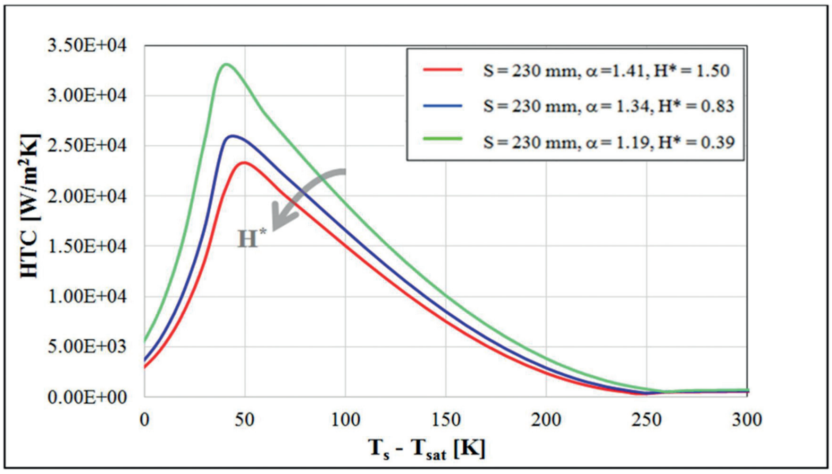

Fig. 6 - Heat transfer coefficient as a function of the distance ratio (H*)

To investigate the influence of the distance between the nozzles on the HTC, a further analysis was performed fixing the diameter of the shaft and changing the relative position of the two uprights (S).
The reduction of the distance between the nozzles enlarges the overlapping area, determining a higher amplification factor and, consequently, a higher mean overlapping volumetric spray flux.
As shown in Fig. 7 for the H*=0.39 distance ratio, the effect of overlapping of sprays significantly increases the heat transfer coefficient only for high percentage of overlapping, i.e. high amplification factor.

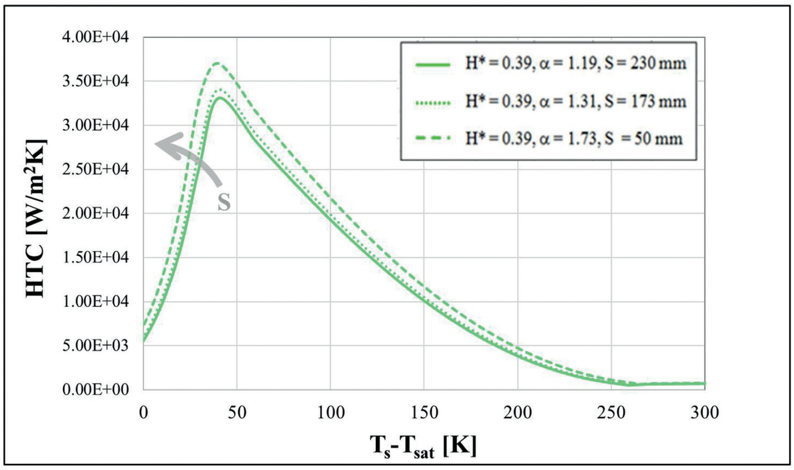

Fig. 7 - Heat transfer coefficient as a function of the distance between nozzles (S)

In case of complex large shaft, characterized by different diameters, both the distance between the uprights and the distance nozzles-part can be adapted to each cross section in order to optimize the cooling. In particular, the quenching of the smaller sections, which otherwise cool down faster than the larger ones, has to be less drastic. This task can be obtained by increasing the distance nozzle-part, to reduce the volumetric flow, or by increasing the distance between the uprights, in order to minimize the overlapping, resulting in a minimisation of the amplification factor as discussed for Fig.7. Concerning the larger sections, the most effective cooling can be reached by approaching the nozzles, as demonstrated in Fig. 6.
By using simulation software and the above mentioned equations for the calculation of the HTC, different attempts can be done to design the optimized spray system configuration for a specific heavy forging shape in order to obtain more homogeneous microstructure and mechanical properties.

CONCLUSIONS

The aim of this paper was to develop a method to estimate the influence of overlapping of sprays on the heat transfer coefficient during quenching of heavy forgings. This method is based on the definition of an amplification factor α which allows to calculate in a simplified way the heat transfer for the whole impingement area with one mean volumetric flux.
According to this amplification factor, it is possible to determine the influence of both the distance between adjacent nozzle and the distance nozzles-part on the heat transfer coefficient and, consequently, to apply the proper boundary conditions in numerical simulation of quenching processes, allowing the optimization of the spray system configuration for a specific forging. A case study of a cylindrical part characterized by different diameters shows the use of the proposed method.

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REFERENCES

[1] V. Schulze, O. Vöhringer and E. Macherauch, "Residual Stresses after Quenching," in Quenching theory and technology, New York, Taylor and Francis Group, LLC, 2010, pp. 229-289.
[2] G. E. Totten, Steel Heat Treatment: Metallurgy and Technologies, New York: Taylor and Francis Group, LLC, 2006.
[3] I. Mudawar and T. Deiters, "A universal approach to predicting temperature response of metallic parts to spray quenching," International journal of heat and mass transfer, vol. 37, no. 3, pp. 341-362, 1994.
[4] A. Pola, M. Gelfi and G. La Vecchia, "Simulation and validation of spray quenching applied to heavy forgings," Journal of Materials Processing Technology, vol. 213, no. 12, pp. 2247-2253, 2013.
[5] I. Mudawar and W. Valentine, "Determination of the local quench curve for spray cooled metallic surfaces," Journal of Heat Treating, vol. 7, no. 2, pp. 107-121, 1989.
[6] K. Estes and . I. Mudawar, "Correlation of Sauter mean diameter and critical heat flux for spray cooling of small surfaces," International Journal of Heat and Mass Transfer, vol. 38, no. 16, p. 2985–2996, 1995.
[7] N. Mascarenhas and I. Mudawar, "Analytical and computational methodology for modeling spray quenching of solid alloy cylinders," International Journal of Heat and Mass Transfer, vol. 53, no. 25-26, pp. 5871-5883, 2010.
[8] I. Mudawar and K. Estes, "Optimizing and predicting CHF in spray cooling of a square surface," Journal of Heat Transfer, vol. 118, p. 672–679, 1996.
[9] R. Chen, L. Chow and J. Navedo, "Effects of spray characteristics on critical heat flux in subcooled water spray cooling," International Journal of Heat and Mass Transfer, vol. 45, p. 4033–4043, 2002.
[10] W. Klinzing, J. Rozzi and I. Mudawar, "Film and transition boiling correlations for quenching of hot surfaces with water sprays," Heat Treat , vol. 9, p. 91–103, 1992.
[11] J. R. Rybicki and I. Mudawar, "Single-phase and two-phase cooling characteristics of upward-facing and downward-facing sprays," International Journal of Heat and Mass Transfe, vol. 49, no. 1–2, pp. 5-16, 2006.