Spray water cooling heat transfer under oxide scale formation conditions

R. Viscorova[1], R. Scholz[2], K.-H. Spitzer[1] and J. Wendelstorf[1]
[1] Institute of Metallurgy, Clausthal University of Technology, Germany
[2] Institute for Energy Process Engineering and Fuel Technology, Clausthal University of Technology, Germany

Abstract

Spray water cooling is an important technology used for the cooling of materials from temperatures up to 1800K. The heat transfer coefficient (HTC) in the so-called steady film boiling regime is known to be a function of the water mass flow density. Below a specific surface temperature T_L, film boiling becomes unstable and the HTC shows a strong dependence on temperature (Leidenfrost effect). The HTC was measured by an automated cooling test stand (instationary method). Compared to the previous state-of-the-art, an additional temperature dependency in the high temperature regime was found. A new analytic fit formula for the dependence of the heat transfer coefficient on temperature and water impact density is proposed and discussed.

Spray water cooling of steel materials at temperature levels above 1000K introduces additional effects due to the formation of oxide layers (scale). These effects and experiments under scale formation conditions will be presented and discussed.

Keywords: scale formation, spray water cooling, continuous casting, hot rolling, heat transfer coefficient.

1 Introduction

Spray water is used for cooling in steel materials production processes, e.g. as part of the casting and rolling procedure. Due to the high temperatures the steel surface is oxidized. A lack of knowledge about the influence of this oxide layer (scale) on heat transfer conditions may prevent a quantitative prediction of the cooling procedure. For predictable homogenous cooling, the dependence of the heat transfer coefficient (HTC) on its principal parameters, the surface temperature

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and the water mass flow density, is required even in the case of oxidized steel surfaces.

The interrelationship between oxide scale formation and heat transfer also determines the temperature of the metal surface. The layer of the oxide scale forms a resistance for the heat transfer. Additionally, due to the cooling process, mechanical tensions arise between the oxide layer and the bulk material which lead to spallation of the scale and thus again to changes of the heat transfer conditions.

For quantitative description, the concept of the Heat Transfer Coefficient (HTC, α) is used, which is defined through its relation to the heat flow density to the surface q [W/m^2] (see also Figure 1):

$$q = \alpha \cdot (T_S - T_W) \tag{1}$$

For spray water cooling, T_W is the water temperature, while T_S is the (local) surface temperature. This approach is most suitable for situations were α is constant, i.e. not depending on $\Delta T \equiv T_S - T_W$. It can also be used for any general heat flow q by using a function for α depending on the same parameters as q. In the so-called steady film boiling regime, α is known to be a function of the water mass flow density [1, 2, 3, 4]. Below a specific surface temperature $T_{S,L}$, the heat transfer coefficient shows a strong dependence on temperature (Leidenfrost effect [5]).

In this paper, the heat transfer coefficient was measured by an automated cooling test stand (instationary method, see Figure 2 and the discussion in [1]) under oxidizing and non-oxidizing sample surface conditions. Additionally, the measurement precision was taken into account (see e.g. [1]). This paper continues the work started in [4].

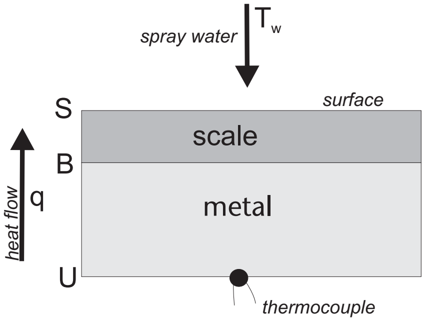

Figure 1: Heat transfer to an oxidized sample.

2 Experimental procedure

The thin sheet specimens of cold rolled metals with a thickness from 1.0-1.5 mm were milled to discs with 70 mm in diameter. Up to 5 thermocouple pairs, one in

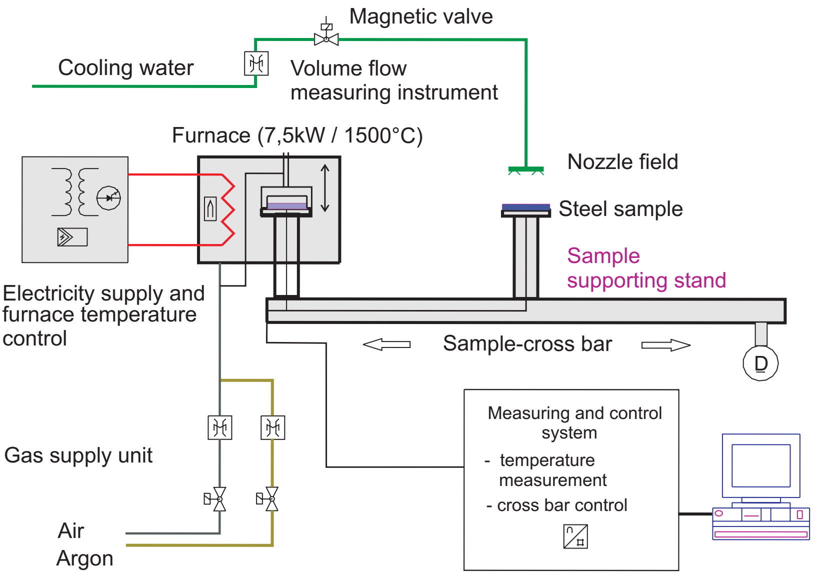

Figure 2: Sketch of the experimental set-up.

the center and the others perpendicular at a radius of 10 mm, were spot welded to the lower side of the sample discs. The temperature measurement was carried out with Ni-CrNi thermocouples with a wire diameter of 0.5 mm. The thermocouple wires were isolated by thin ceramic tubes. The experimental set-up sketched in Figure 2 was used for heating, oxidizing the samples and measurement of the temperature during spray cooling.

After installation in the furnace sample holder, the disks were heated up to 1200 °C under protective atmosphere. For the measurements with scale, the samples were oxidized in the furnace by supplying air instead of protective gas for a specific time and temperature. Reaching the test conditions (temperature, oxidation time), the sample was moved automatically from the furnace under the full cone nozzle which takes approximately 4 seconds and subsequently cooled with spray water. The spray water mass flow density V_S was determined experimentally and varied in the range of about 4 ± 1 to 30 ± 1 kg m^2 s^{-1}. The water temperature T_W was approximately 18 °C. The materials investigated were commercially pure Nickel (99.2% Ni) and Iron (low-carbon steel, AISI 1008, 99.7% Fe).

3 Measurement of the HTC at elevated temperatures

For the investigation of the HTC from a non oxidized surface, Nickel material was used, because surface oxidation is minimized, and the physical properties are known within the temperature range being studied. The samples were annealed at 1200 °C and consequently cooled. The cooling curves were measured at three points for each sample as described above. Figure 3 shows typical cooling curves of the Nickel specimens for different water mass flow densities. The sample reaches the spray water cooling position after about 4.2 s. The cooling starts in the range of stable film boiling. The primary effect of the water mass flow density V_S can be seen by comparing the different cooling curves. When increasing V_S from 4 up to 30 kg m^2 s^{-1} the sample cooling rate increases. At approximately 300-450 °C, dependent on V_S, the cooling curves bend. At this point the Leidenfrost temperature is reached and more rapid cooling begins (unstable film boiling).

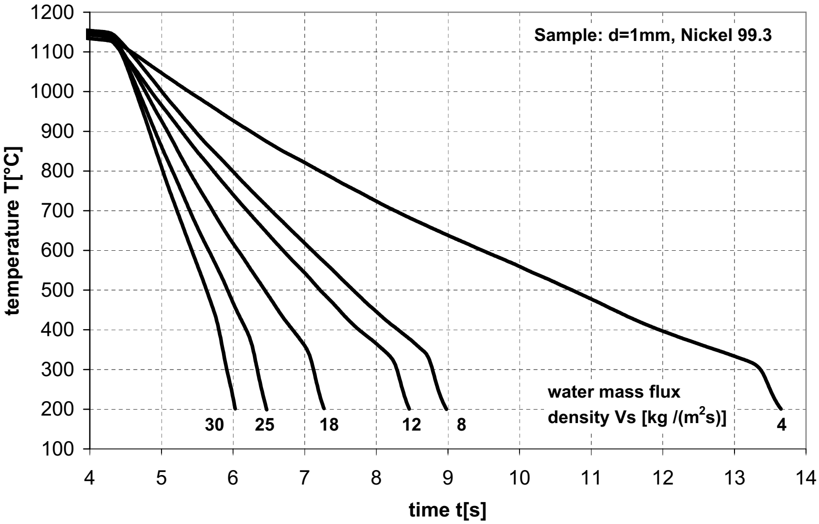

Figure 3: Cooling curve for different water mass flow densities V_S (spray water cooling of pure Nickel).

For each cooling curve (V_S-value), $\alpha(T_S)$ is obtained from the following equation:

$$\alpha(T_S) \approx -\frac{\rho \cdot c_p(T_U) \cdot d}{T_U - T_W} \cdot \left.\frac{\partial T_U}{\partial t}\right|_{z=0} \tag{2}$$

with:

α	heat transfer coefficient	[W m^{-2} K^{-1}]
c_p	specific heat capacity of the sample ($= f(T)$!)	[J kg K^{-1}]
d	thickness of the sample	[m]
z	vertical coordinate (bottom: $z = 0$,U; top: $z = d$,S)	[m]
t	time	[s]
ρ	mass density of the sample	[kg m^{-3}]
T_U	temperature measured at the lower side (U, Fig.1)	[K]
T_W	temperature of the spray water	[K]

Equation (2) is valid for thin samples such as in this case ($d = 1$ mm) because of the small temperature difference between the cooled top and the measurement point at the bottom ($\approx 10\,^\circ$C in the stable film boiling regime). The specific heat capacity c_p of the sample materials depending on temperature was calculated with the Thermocalc Software based on the chemical analysis. A fit function describing the $\alpha(\Delta T, V_S)$ dependence was calculated from the measurement data

$$\alpha(\Delta T, V_S) = \text{erf}\left(\frac{V_S}{5}\right) \times \Bigg(245 \cdot V_S \left[1 - \frac{V_S \cdot \Delta T}{58223}\right] + 4.3 \cdot \Delta T^2 \left\{1 - \tanh\left(\frac{\Delta T}{115}\right)\right\}\Bigg) \quad (3)$$

and is shown in Figure 4. In the open literature, the HTC in the range of stable film boiling (i.e. above $\Delta T = 600$K) is assumed to be independent of the surface temperature. As shown in Figure 4, for the higher spray water densities, $V_S > 15$ kg m^{2}s^{-1} there is a decrease in the measured HTC even in the stable film boiling regime. This effect may be explained with an increasing vapor layer thickness and yields to α-contours no longer parallel to the ΔT-axis.

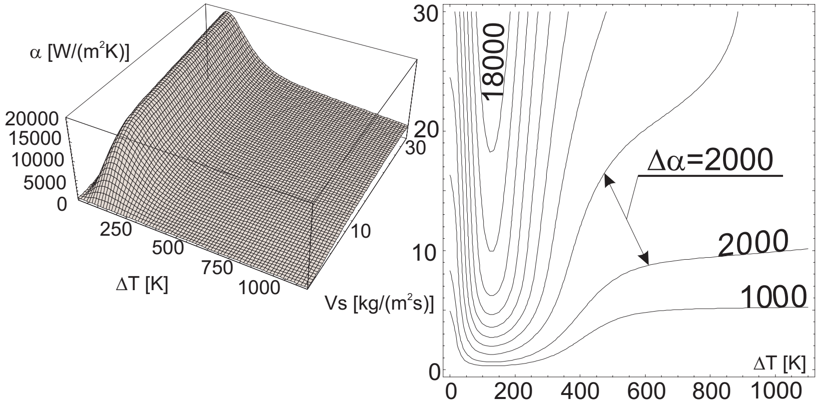

Figure 4: Heat transfer coefficient after eq. (3) in dependence on temperature difference and water mass flow density.

4 The HTC for an oxidized surface

Following the initial considerations and the basic knowledge on scale properties (e.g. [4]), the determination of the influence of scale on the heat transfer conditions introduces some difficulties due to the following reasons:

- Thin scale layers ($< 10\ \mu$m) may show enough adhesion for measurement but imply a very small heat resistance.
- Small gas layers between the scale and the substrate (blistering) imply a big effect on heat resistance (*random effect*).
- The adhesion of medium thickness scale layers ($10 \ldots 200\ \mu$m) may be not sufficient to withstand spray water – spallation and descaling occurs (*instationary effect*).
- Thicker scale layers ($> 200\ \mu$m) are removed rapidly by the spray water – the thermal effect becomes inhomogeneous.

Regardless these difficulties, the practical importance remains and thus the influence of an oxide layer on heat transfer was investigated in a second set of experiments in which the low alloy material AISI 1008 (99.7% Fe) was used. In order to get well defined scale formation, the oxidation kinetics was determined in the first step [6]. These investigations allow to calculate the scale layer thickness from the oxidation temperature and time.

4.1 Modelling of the HTC for an oxidized surface

For understanding the influence of an oxide layer on the heat transfer during spray water cooling, the mechanism of heat transfer at an oxidized surface is theoretically described first. Since calculations often can not include thin layer effects, an effective heat transfer coefficient containing all scale layer effects is introduced. The heat flow is thus described by an effective heat transfer coefficient which is using the temperature difference between the steel surface and the temperature of the water (see Figure 1):

$$q = \alpha_{\text{eff},\Delta T = T_B - T_W} \cdot (T_B - T_W) \tag{4}$$

q	heat flow density	[W m^{-2}]
α_{eff}	effective heat transfer coefficient	[W m^{-2} K^{-1}]
T_B	temperature at the steel-scale interface	[K]

The heat transfer from the surface to the spray water is given by

$$q = \alpha_{\Delta T = T_S - T_W} \cdot (T_S - T_W) \tag{5}$$

and the heat transfer through the oxide layer can be approximated by

$$q = \frac{\lambda_{sc}}{\delta_{sc}} \cdot (T_B - T_S) \tag{6}$$

λ_{sc}	effective heat conductivity of the scale	[W m^{-1} K^{-1}]
δ_{sc}	thickness of the scale layer	[m]
T_S	temperature at the surface of the oxide scale	[K]

Under quasi-stationary conditions and for uniform cooling, the heat flow (4) from the surface to the cooling water (5) is equal to the heat flow through the scale layer (6) and we get the effective HTC defined by (4):

$$\alpha_{\text{eff},\Delta T=T_B-T_W} = \left(\frac{1}{\alpha_{\Delta T=T_S-T_W}} + \frac{\delta_{sc}}{\lambda_{sc}}\right)^{-1} \tag{7}$$

The effective heat transfer coefficient α_{eff} contains the influence of the oxide layer (thermal insulation, temperature drop). It can be calculated by (7) using the HTC $\alpha(\Delta T = T_S - T_W, V_S)$, which does not depend on bulk material properties. So accurate measurements of $\alpha(\Delta T = T_S - T_W, V_S)$ without scale can be used for surfaces with well defined oxide layers. Additionally, a measurement using an oxidized surface and (2) for analysis will yield to a *measured* α_{eff}. The function $\alpha_{\text{eff}}(\Delta T = T_B - T_W, V_S)$ calculated from (7) using the fit-formula $\alpha(\Delta T = T_S - T_W, V_S)$ from (3) is shown in Figure 5 and discussed below.

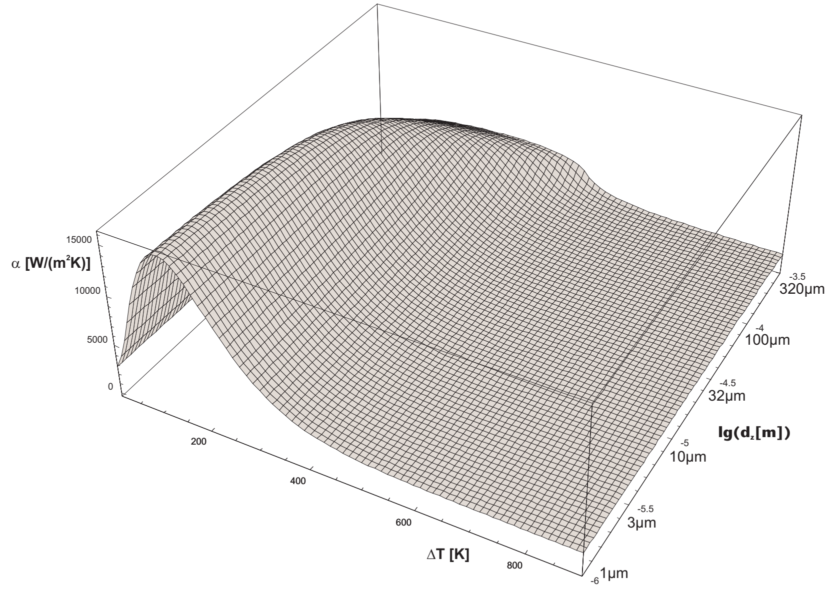

Figure 5: Calculated effective heat transfer coefficient depending on temperature difference $\Delta T = T_B - T_W$ and oxide layer thickness (logarithmic scale).

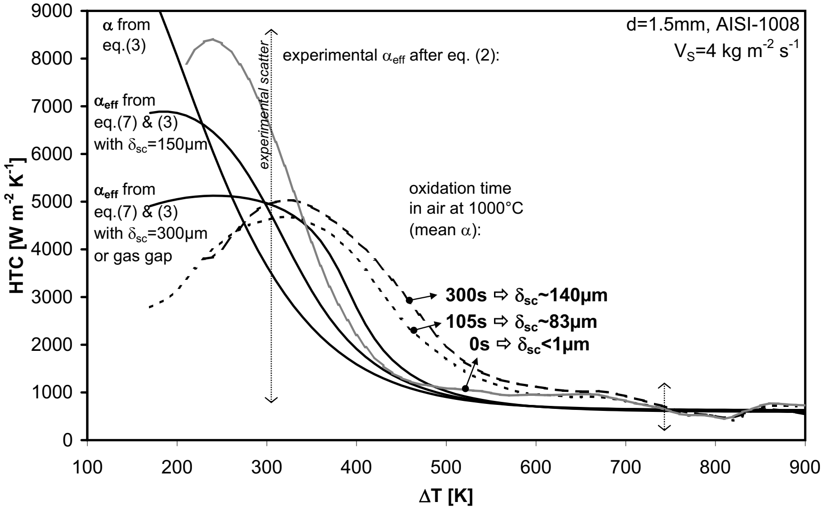

Figure 6: Predicted and measured α_{eff} in dependence on $\Delta T = T_B - T_W$ for different oxidation times or scale layer thicknesses.

4.2 Measurement of the effective HTC

The *predicted* effective HTC for an oxidized sample is compared with experimental data in Figure 6. Low alloy steel (AISI 1008) samples and a water mass flow density of $V_S = 4$ kg m^{-2} s^{-1} were used. The measured cooling curves are analysed by calculating α_{eff} using eq. (2). The first observation is a larger experimental scatter for oxidized samples, especially in the unstable film boiling regime. For this reason all available cooling curves were individually analysed and the mean values $\bar{\alpha}_{\text{eff}}$ are plotted (dashed lines). The corresponding scale layer thicknesses were calculated from the given oxidation times using a parabolic growth law [6].

The heat transfer in the stable film boiling regime is not influenced by the scale layers, as expected. At lower temperature differences $\Delta T = T_B - T_W$, the heat transfer increases, the Leidenfrost phenomenon starts at higher ΔT values, but the maximum α_{eff} values are smaller. Assuming a scale layer thickness of 150 and 300 μm and a heat conductivity of λ_{sc}=3 W m^{-1}K^{-1}, the calculated α_{eff} is also plotted (solid lines). The agreement is better by assuming a larger scale layer thickness than calculated from the oxidation time. This finding is in accordance with the assumption of a thin gas/vapour layer between scale and metal surface. Due to the much lower heat conductivity of this film, the apparent effect is that of a much thicker scale layer.

These theoretical and experimental investigations indicate a change of α_{eff} with increasing surface oxidation mainly in the unstable film boiling regime. The apparent temperature corresponding to the Leidenfrost point $T_{S,L}$ shifts to higher values.

In the range of stable film boiling, the α_{eff} values are approximately equal to α, as long as $\frac{\lambda_{sc}}{\delta_{sc}}$ is much greater than α.

The experimental findings show qualitative agreement with the calculations. The local change in the sample surface state yields a more random local heat transfer. The smaller heat conductivity of the scale layer implies its more rapid cooling and thus a faster onset of unstable film boiling for oxidized surfaces (increasing α_{eff}). Especially in the stable film boiling regime, the isolation of the scale layer from the metal surface by a small gas or vapour film may imply a decreasing α_{eff}. As a consequence, spatial inhomogeneous heat removal from the surface will cause heat flows by conduction parallel to the surface plane. These α_{eff} *measurements* are thus not as accurate as the measurements without surface oxidation. The current measurements are estimated to be accurate within $\pm 25\%$ for the determination of the HTC while the literature data is estimated to have about $\pm 40\%$ accuracy in the stable film boiling regime. Below $\Delta T \approx$ 500K, approaching the Leidenfrost point, the measurements are somewhat less accurate. For oxidized surfaces showing descaling during cooling, the local HTC fluctuates randomly. The statistics of this behaviour needs to be investigated in greater detail. Without blistering, stable adhesive scale surface layers need to grow thicker than $\approx 150\ \mu$m in order to influence the local heat transfer coefficient (7).

5 Summary and conclusions

In this study, spray water cooling of different materials from initial temperatures up to 1200 °C was investigated. The (low alloy) AISI-1008 steel and – for comparison – Nickel was used for the experiments. The heat transfer coefficient was measured by an automated cooling test (instationary method). This allows for a determination of the HTC depending on the surface temperature T_S, within a single experiment. The second parameter, the water mass flow density V_S, was varied from 4 to 30 kg $\text{m}^{-2}\text{s}^{-1}$. Furthermore, spray water cooling of steel materials introduces additional effects due to the formation of oxide layers (scale). For the investigation of these effects, steel samples were oxidized in air at different temperatures and for specific times. Finally, the HTC was measured for oxidized samples. For the assessment of the scale layer effect and application purposes, an effective heat transfer coefficient α_{eff} was defined. Summarizing, the following effects where observed

- An additional temperature dependency in the high temperature (stable film boiling) regime was found, thus the HTC is also temperature-dependent above the Leidenfrost temperature - simple $\alpha(V_S)$-relations are very inaccurate.
- A new fit formula for the recommended $\alpha(\Delta T, V_S)$ is provided.
- For the quantitative description of the oxide scale formation, spallation has to be taken into account.
- In the lower ΔT (unstable film boiling) regime, scale layers can dramatically influence the apparent HTC.

- The oxide layers can impede heat transfer by random formation of an isolating gas gap between the oxide and the bulk material (blistering).
- Spallation of the oxide scale and thus scale plates moving around, additionally influence local and global cooling conditions.

As a conclusion, the heat transfer coefficient (HTC, α) introduced by (1) and approximated from experimental data (eq. (3) and Figure 4) is a complex function of the surface temperature, the water mass flow density and the surface condition.

Acknowledgements

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References

[1] N Lambert and M Economopoulos. Measurement of the heat-transfer coefficients in metallurgical processes. *Journal of the Iron and Steel Institute*, 208:917–928, 10 1970.

[2] U Reiners, R Jeschar, R Scholz, D Zebrowski, and W Reichert. A measuring method for quick determination of local heat transfer coefficients in spray water cooling within the range of stable film boiling. *steel research*, 56(5):239–246, 1985.

[3] M Bamberger and B Prinz. Determination of heat transfer coefficients during water cooling of metals. *Materials Science and Technologie*, 2:410–415, 4 1986.

[4] C Köhler, R Jeschar, R Scholz, J Slowik, and G Borchardt. Influence of oxide scales on heat transfer in secondary cooling zones in the continuous casting process, part i.&ii. *steel research*, 61(7):295–301 & 302–311, July 1990.

[5] B S Gottfried, C J Lee, and K J Bell. The leidenfrost phenomenon: Film boiling of liquid droplets on a flat plate. *International Journal of Heat and Mass Transfer*, 9:1167–1187, 1966.

[6] R Viscorova, R Scholz, K H Spitzer, and J Wendelstorf. In *AISTech 2006, May 1-4, 2006, Cleveland, Ohio, USA*. AIST, 2006.