THE HEAT TRANSFER COEFFICIENT AT DISCONTINUED WATER SPRAY COOLING

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Abstracts

Cooling by water sprays is widely used in heat treatment and other metallurgical processes to control the process temperature. Water spray cooling is used statically (without movement of the spray nozzles relative to the cooled object) or dynamically (with the movement). The static regime is typical for quenching systems intended for heat treatment of fixed steel plates. The dynamic regime is used in steel treatment processes such as rolling and finishing in mills. The movement of the steel plate relative to the fixed cooling section causes non-homogeneous distribution of water on the surface of the steel plate. The variability of the cooling section length, position of water nozzles and non-homogeneity of water distribution lead to non-uniform and distorted cooling conditions. Thus it is an important issue to define the impact of these parameters on cooling intensity and the heat transfer coefficient during the cooling process of steel plates. Heat treatment of high-temperature steel is held without protective atmosphere and is accompanied by growth of different oxides on the steel plate surface as well. The layer of oxides significantly affects the cooling regime and intensity. The influence of the oxide scales on the cooling intensity was studied experimentally and by numerical modeling for different cooling regimes. Experiments were conducted for static and dynamic regimes on surfaces with different rate of oxides layer. Prepared numerical analysis simulates the process with different conditions of the cooling section and samples with different oxide scale layers. Results obtained by numerical simulation approved the impact of the oxide layer on the cooling intensity and shown different character in the static and the dynamic regime.

Keywords: Numerical simulation, heat flux, heat transfer coefficient, oxide layer, water spray cooling

1. INTRODUCTION

Spray cooling is a common cooling method used in steel processing, especially for product cooling, heat treatment, roll cooling and in a secondary cooling zone in the continuous casting of the steel. The cooling intensity and its homogeneity on the cooled surface affects final quality of the steel product and mechanical properties of the steel such as grain size, yield strength, ultimate strength and so on. Method of spray cooling and its intensity can be designed according to specific applications. Spray cooling intensity is affected by many factors such as water impingement density [1, 2], water temperature, velocity of sample movement [3] and surface roughness [4]. The heat transfer during spray cooling of hot surface with a temperature significantly hotter than the liquid's boiling point to the surrounding water is characterized by four different cooling regimes (film boiling, transition boiling, nucleate boiling and single-phase liquid cooling). Starting the observation from the high temperature regime a stable vapor film forms between the water film and the surface. The film boiling regime persists to a lower temperature limit, known as the Leidenfrost point. Minimum liquid/solid interface temperature required to support film boiling is called the Leidenfrost temperature. This temperature occurs, when the heat flux reaches minimum on the boiling curve [1].

Oxidation is an integral part of steel production and heat treatment. Oxide layers commonly impact surface quality and material losses during steel processing. The oxide layer also affects the cooling process. The oxide layer forms porous layer on the metal surface. This oxide layer has a very low thermal conductivity compared to the metal and acts as a thermal barrier. This thermal barrier lowers the heat flux from the metal surface to the surroundings when cooling with constant intensity, as with the air cooling. The use of water can cause that an oxide layer does not only serve as insulation, but can also intensify the spray cooling for a short time period [5]. The oxidation level is known to influence the onset of transition boiling for the immersion cooling [4]. Several authors [5, 6] have investigated the influence of the oxide layer on the heat transfer coefficient during water spray cooling with static nozzle and static test sample. They observed that the Leidenfrost temperature increases with the increase of the oxide layer thickness [5] and the critical heat flux decreases with the increase of the oxide layer thickness [6]. It is known that the velocity of the sample movement under static nozzles influence the heat transfer during spray cooling [3] and so it can be expected that the influence of the oxide layer on the cooling intensity can differ for static (static regime) and moveable sample (dynamic regime). This paper is focused on studying the impact of the oxide layer on the cooling intensity at static and dynamic regimes.

2. EXPERIMENTAL MEASUREMENT

The experimental measurement of impact of the oxide scale layer on the cooling intensity during dynamic regime was prepared. Different thicknesses of the scale layer were created on the test plate made of austenitic stainless steel. Two different areas (areas A and B) with different scale layer thicknesses were prepared on the test plate surface. The experimental procedure consisted of several steps to reach the relevant experimental data of cooling process with oxide scale layers. A laboratory stand to test the cooling intensity with different levels of oxide layer on the surface was used. The temperature was measured by eighteen thermocouples (T1-T18). The two thermocouples in areas A and B (T4 and T5) were used for the comparison of the scale layer effect. Three flat jet nozzles with typical use in the secondary cooling zone in the continuous casting of the steel were positioned on the moveable mechanism under the test plate. Nozzles moved at a velocity 1 m min^{-1} under static test plate. The test plate on initial temperature 980 °C was heated. Nozzles moved in one direction with opened deflectors and returned with closed deflectors in defined positions. This was repeated until the temperature in all measured points was cooled below 100 °C. More details about experimental measurement is described in [7].

The thickness of the scales was measured after the experiment. Two scales samples were taken from test plate after the experiment. One from area A and one from area B. The scale layer from area A was partly removed during cooling and was much thicker than the scale layer in area B. The scale layer which grew on the pickled area was approx. 50 µm thick and was very porous (30 % of the air). The scale layer in the area B was not so homogeneous as in the area A and the thickness differs from 0 µm to 50 µm.

An inverse task [5], [6] was used to calculate measured temperatures (see **Fig. 6**) to surface temperatures for evaluation of the heat transfer coefficient. The dependence of the heat transfer coefficient on the surface temperature is shown in **Fig. 1** for thermocouples T4 and T5. The Thermocouple T4 was located in the area A (area with thick porous scale layer and thermocouple T5 was located in the area B (thin inhomogeneous scale layer). The heat transfer coefficient is almost the same for thermocouples T4 and T5 for surface temperatures higher than Leidenfrost temperature (840 °C). The Leidenfrost temperature was significantly higher for the thermocouple T4, which was located in the area with thick porous scale layer. The Leidenfrost temperature was 840 °C for thermocouple T4 and 600 °C for thermocouple T5.

The temperature in which the maximum heat transfer coefficient occurs was higher for thermocouple T4. The maximum heat transfer coefficient occurs at 400 °C for thermocouple T4 and at 250 °C for thermocouple T5. There was no significant difference between thermocouples T4 and T5 in the value of the reached maximum heat transfer coefficient (approx. 3600 W m^{-2} K^{-1} and 3900 W m^{-2} K^{-1}).

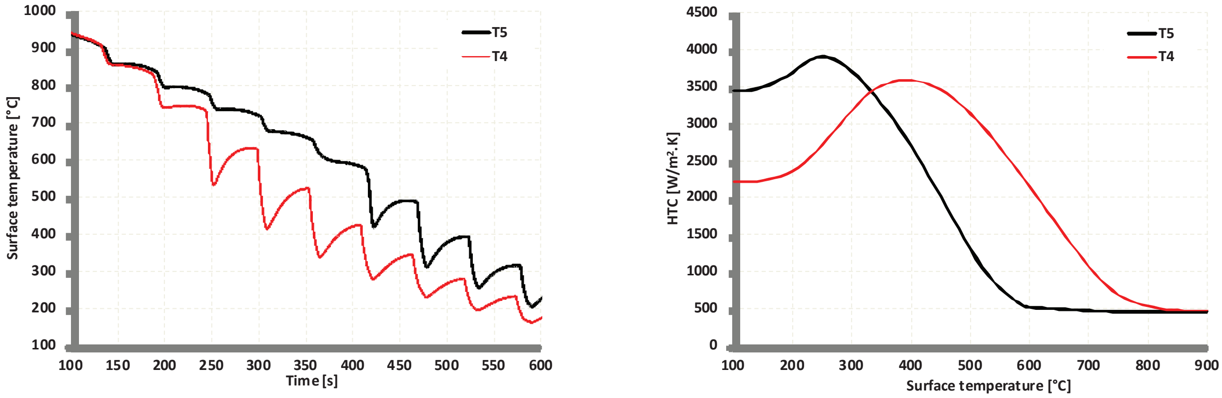

Fig. 1 Measured temperatures in the thermocouples T4 and T5 (left) and heat transfer coefficient (right)

3. NUMERICAL SIMULATION

The numerical simulation was prepared to study the oxide scale layer on the cooling process at two different regimes and two different thermal conductivities of the oxide layers. The first regime represents the static cooling process. The test plate is without movement. The static regime is characterized by continues cooling conditions. The second regime was described as dynamic. The dynamic cooling process is typical by moving of the test plate. The numerical simulation was based on the experimental measurements described in the previous chapter.

3.1. Numerical model

The numerical model was based on the Finite element method (FEM) and the model was created as two dimensional. The two basic cases of the FE model corresponding with measured specimens were created. The first case composed only from the base material (structural steel). In the second case, the FE model included the base material and defined oxide scale layer. Three thicknesses of the oxide scale layers were considered in the numerical model (30, 50, 100 μm). For all the thicknesses two values of thermal conductivities of oxide layers were applied. For the base material the physical properties of structural steel were applied. For the oxide scale layer the physical properties from literature were used which occur in large dispersion (0.1-3 W/mK). The thermal conductivity 0.2 and 1.0 W/mK was applied. The physical properties of steel and oxide scale applied in FE model are shown in **Table 1**.

Table 1 Material properties

Thermal conductivity	Specific heat	Density
Oxide scale		
0.2; 1.0 W/mK	970.0 J/kgK	5700.0 kg/m^3
Structural steel		
60.0 W/mK	434.0 J/kgK	7850.0kg/m^3

The material of the steel and oxide scale was considered as continuous and homogenous. From experimental measurement the curve of HTC vs. surface temperature for all considered variants was applied. Measured heat transfer coefficient used in numerical modelling is depicted in **Fig. 1** (line T5). In the FE model the ambient temperature 22 °C was used. This temperature corresponds with temperature of the cooling water used in experimental measurement. In the FE model initial temperature 900 °C was applied. This temperature was initial temperature during the measurement. The numerical analysis of static regime was loaded by HTC curve. The cooling time in numerical simulation was defined to 370 s. In the dynamic regime two load cases alternate. The first load case consists of cooling (HTC curve was applied) and in the second case the radiation was used.

The radiation was considered between the surface of the plate and the ambient temperature. The value of emissivity was defined to 1.0 and the ambient temperature was 22 °C. The first load case was defined on 10 s and duration of the second case was 15 s. The total time was 540 s.

3.2. Results of numerical analyses

The results were evaluated for both regimes. The evaluation was carried out in contact between the base material and the oxide layer. The evaluation of results was performed on surface temperature of steel Ts. The same symbols were applied on the heat fluxes. Heat flux through steel surface is marked Qs. The schematic illustration of evaluated location from numerical simulation is presented in **Fig. 2**. Based on evaluated values of the surface temperatures (Ts) and heat fluxes from surface (Qs) the heat transfer coefficient (HTC) was calculated.

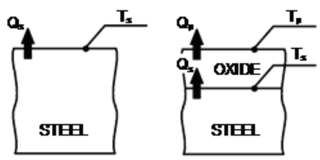

Fig. 2 Evaluated position in FE model

The evaluation of the temperatures for both regimes and different thickness are presented in **Fig. 3** and **4**. The presented results of temperature history confirm the impact of the static and dynamic cooling regime and also the impact of the different thickness of the oxide layer. If we apply static cooling regime we can reach lower temperature earlier than if we use dynamic regime. In dynamic regime we need more time to cool down because we apply the cooling only for defined time interval and during the time without cooling the temperature is recovered due to thermal energy inside the sample. The clean steel surface was considered as reference. From the results it is possible to see that the temperature in the dynamic regime after 40% longer cooling time does not reach the same final temperature as in the static regime. This effect is more significant in temperatures obtained from oxide layer. The static regime seems to be cooling more intensively than the dynamic regime. In the static regime the intensity of cooling is affected by the oxide layer. It is evident, that the thickness of the oxide layer shifted the Leidenfrost temperature in time. The assumption from introduction was approved. Firstly, the Leidenfrost temperature was reached at the thickest oxide layer. On the clean surface it was the latest. This is caused by insulation character of the oxide layer which led to quick cooling of the oxide layer and blocked the flow of thermal energy from steel. For all considered cases this effect was confirmed. The intensity of cooling in the dynamic regime is also affected by the length of the cooling interval compared to time without cooling (only radiation). The combination of thickness of the oxide layer and cooling interval could have important influence on the cooling intensity and the cooling time. Two parameters (heat flux and HTC) were applied to study the impact of the oxide layer and cooling regime on the cooling intensity. The evaluated heat fluxes and HTC for considered cases are depicted in **Fig. 3 and 4**. The heat flux curves for dynamic regime were constructed from the maximum values of the heat fluxes of the cooling interval. For each oxide layer thickness and also for clean steal surface the maximum heat flux in time was evaluated and the heat flux curves vs. time were created. These curves can possibly be directly compared with heat flux curves evaluated from the static regime. The comparison of both regimes at both values of the scales conductivities are presented in **Table 2 and 3**. In these tables the differences between the static and the dynamic regime of evaluated parameters (heat flux and HTC) were carried out. From presented results it is evident, that we can find cases in which the dynamic regime reached more intensive cooling than the static regime. More intensive cooling of the dynamic regime was found for scales with lower thermal conductivity (0.2 W/mK). The heat flux for the dynamic regime was about 0.1-3 % higher for all thicknesses and HTC reached values about 3 % higher for thickness 30 μm and 100 μm. Lower thermal conductivity corresponds with nonhomogemous and discontinued structure of scale layer. For higher thermal conductivity the heat fluxes were slightly higher for the dynamic regime but the HTC was lower for all thicknesses. Higher value of thermal conductivity is closer to case without base material and therefore the impact of the scales is less significant. The difference in the heat fluxes and HTC between the static and the dynamic regime cannot be neglected.

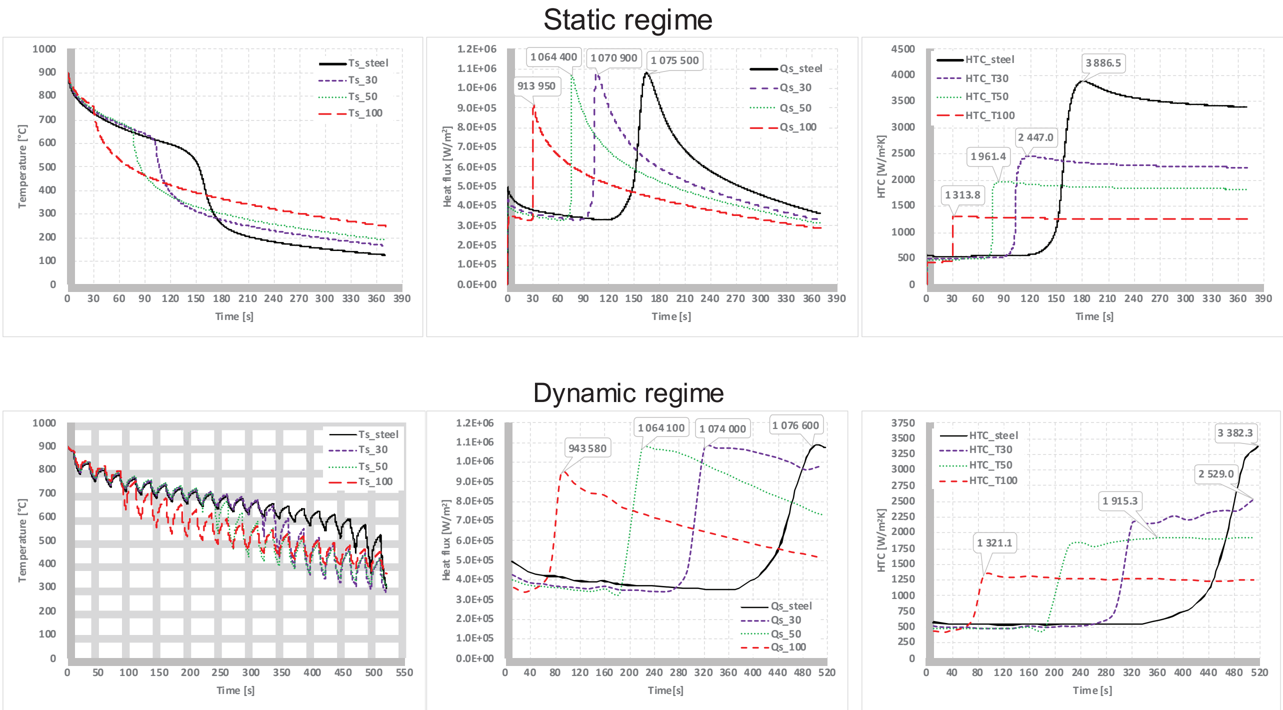

Fig. 3 Evaluation of the results for thermal conductivity 0.2 W/mK

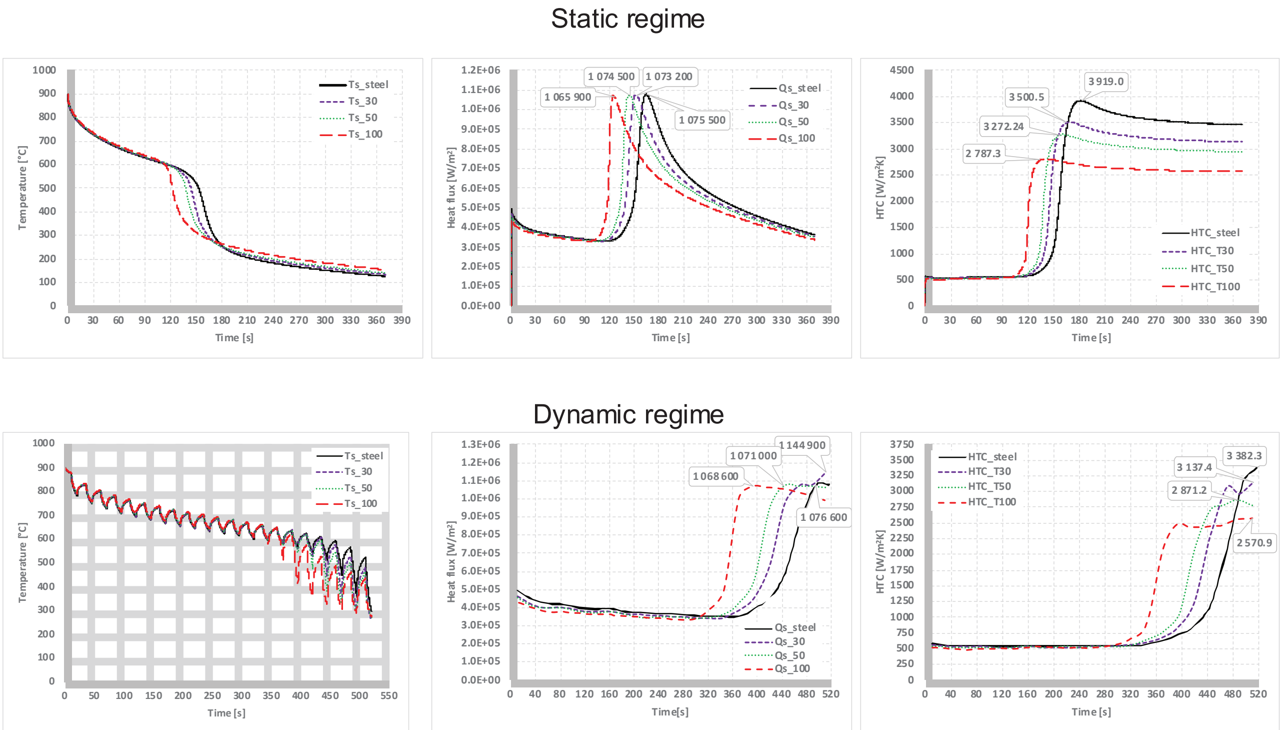

Fig. 4 Evaluation of the results for thermal conductivity 1.0 W/mK

Table 2 Maximum values of the heat flux and HTC for thermal conductivity of scales 0.2 W/mK

	Static regime		Dynamic regime		Difference	
Scale thickness [μm]	Heat flux [W/m^2]	HTC [W/m^{2}K]	Heat flux [W/m^2]	HTC [W/m^{2}K]	Heat flux [%]	HTC [%]
clean steel	1075500.0	3919.9	1076600.0	3382.3	100.1	86.3
30	1070900.0	2459.7	1074000.0	2529.0	100.3	102.8
50	1064400.0	1969.4	1064100.0	1915.3	100.0	97.3
100	913950.0	1313.8	943580.0	1321.1	103.2	100.6

Table 3 Maximum values of the heat flux and HTC for thermal conductivity of scales 1.0 W/mK

	Static regime		Dynamic regime		Difference	
Scale thickness [μm]	Heat flux [W/m^2]	HTC [W/m^{2}K]	Heat flux [W/m^2]	HTC [W/m^{2}K]	Heat flux [%]	HTC [%]
clean steel	1075500.0	3919.9	1076600.0	3382.3	100.1	86.3
30	1073200.0	3500.5	1144900.0	3137.4	106.7	89.6
50	1074500.0	3272.2	1071000.0	2871.2	99.7	87.7
100	1065900.0	2787.3	1068600.0	2570.9	100.3	92.2

4. CONCLUSION

The experimental and numerical investigation of the oxide scale layer thickness with different properties was performed. The numerical simulations of defined cases were carried out. The results showed and confirmed the following effects. The first effect is shifting of the Leidenfrost temperature in time depending on the thickness of the oxide layer. The second effect is higher cooling intensity at shorter cooling time for static regime in clean steel surface. The third important effect was observed for the dynamic regime with lower thermal conductivity. In this case higher cooling intensity was found compared to the static regime. These results confirm the assumption that the oxide scale layers in combination with properties of scales and during the dynamic regime have higher cooling intensity than the static regime with the same scale layer. These results can possibly be used for the design of cooling sections and to optimization of the cooling process.

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