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Effects of oxide layer on Leidenfrost temperature during spray cooling of steel at high temperatures

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ABSTRACT

Spray cooling is a common cooling method used in many high-temperature metal processes. Using a combined numerical and experimental approach, the influence of the oxide layer on the Leidenfrost temperature during spray cooling of surfaces at high temperatures was investigated. The heat transfer from a metal surface covered by an oxide layer is described using the concept of the effective heat transfer coefficient and this concept is extended to the Leidenfrost temperature. The effective Leidenfrost temperature is introduced. The prediction of the effective Leidenfrost temperature is compared with the numerical simulation and with the experiment, which was conducted on an austenitic stainless steel plate with varied oxide layer thicknesses. The test plate with the oxide layers was heated to 1000 °C and then cooled using flat jet nozzles. The present study confirms that the use of water in the spray cooling of hot surfaces can create a situation where the oxide layer not only serves as insulation but can also increase the cooling intensity for short time period, mainly by a shift of the Leidenfrost temperature.

1. Introduction

Water spray cooling is a common cooling method used in many high-temperature industrial applications, such as metal processing or electronics cooling. Metal processing can include the formation of oxides on the surface. These oxides form a porous layer on the metal surface. The 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 it is cooled by air but the use of water can cause a shift of the Leidenfrost temperature and intensify the cooling for a short time period [1,2].

As described by many heat transfer textbooks [3–5], if a liquid is in near contact with a surface significantly hotter than the liquid's boiling point, the heat transfer boiling phenomena based on the heat flux data or a boiling curve (heat flux versus excess temperature) can be characterized by four different regimes: (a) free convection (single-phase), (b) nucleate boiling, (c) transition boiling and (d) film boiling. Based on the boiling curve, at the onset of the film boiling, the heat flux is minimal (between the transition boiling and film boiling regimes) and the corresponding temperature is known as the Leidenfrost temperature or point. Although the definition of Leidenfrost point was originally based on the heat flux data measured from pool boiling experiments [3–5], the minimum heat flux is also used for the determination of the Leidenfrost point for spray cooling [6–8]. It has been shown that the overall shape of the boiling curve has been similar for bath quenching (immersion cooling) and spray cooling, while the cooling rate in each regime is much greater with spray cooling than with bath quenching [9,10]. Accordingly, the minimum heat flux criterion is adopted for the present spray cooling study in determining the Leidenfrost temperature. Note that the boiling heat transfer process considered here is not a heating process with respect to the liquid but is a cooling process with respect to the hot surface or object.

The Leidenfrost temperature in spray cooling is mainly influenced by the water impingement (spray) density [6,11,12], the water temperature [13] and by the surface roughness [14]. The presence of oxides on the surface changes the surface roughness [15], and so the effect of the oxide layer on the Leidenfrost temperature can also be influenced by the different surface roughness of the oxide free surface and oxidized surface. The oxidation layers have been known to influence the onset of transition boiling for the immersion cooling [14]. Several investigators [16,17] have observed the influence of the oxide layer on the heat transfer coefficient during water spray cooling, but they have not studied the effect of the oxide layer to the Leidenfrost temperature.

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Nomenclature

h	heat transfer coefficient (W m^{-2} K^{-1})
q	heat flux (W m^{-2})
t	time (s)
T	temperature (K)
δ	thickness (m)
h	heat transfer coefficient (W m^{-2} K^{-1})
ζ	sensitivity of the thermocouple
Subscripts	
eff	effective
i, m, f	index
L	Leidenfrost
L_eff	effective Leidenfrost
ox	oxide
p	oxide surface
s	steel surface
min	minimum
∞	ambient

The present paper deals with the change of the Leidenfrost temperature due to the presence of an oxide layer. Further, the influence of the oxide layer on the Leidenfrost temperature is described theoretically and investigated experimentally and by the numerical simulation.

2. Analysis of the oxide layer effect on the Leidenfrost temperature

The heat transfer on the oxidized sample is described by the concept of an effective heat transfer coefficient (EHTC) (h_{eff}) which was introduced by [17,18]. This concept is extended to the Leidenfrost temperature, while an effective Leidenfrost temperature (T_{L_eff}) is also introduced here. The heat conductance of the oxide layer is treated similar to the expressions of the contact conductance and contact coefficient described in the text (pp. 57–60) by Holman [5].

Let q_s e a heat flux from an oxide-free steel surface at temperature T_s to the surroundings at a temperature T_∞ (Fig. 1).

This can be modeled by Newton's Law of cooling:

$$q_s = h(T_s - T_\infty), \tag{1}$$

where h is the heat transfer coefficient (HTC). The heat flux from the oxidized surface q_p at oxide surface temperature T_p is

$$q_p = h(T_p - T_\infty). \tag{2}$$

We define the EHTC (h_{eff}) for the steel surface covered by oxide layer as:

$$h_{eff} = \frac{q_s}{(T_s - T_\infty)}. \tag{3}$$

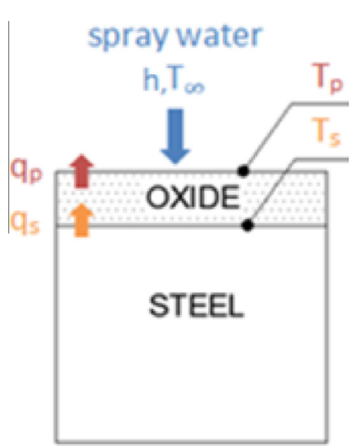

Fig. 1. Schematic of the heat transfer from an oxidized steel surface.

The EHTC contains the isolation effect of the oxide layer on the heat transfer and it can simplify numerical simulations of the cooling process because the numerical model does not need to consider the oxide layer. The oxide layer is very thin compared to the thickness of the substrate and so the heat accumulated in the oxide layer can be ignored ($q_s \approx q_p$). Using Fourier's Law, one has

$$q_p \approx \frac{\lambda_{ox}}{\delta_{ox}}(T_s - T_p), \tag{4}$$

where λ_{ox} is the thermal conductivity of the oxide layer and δ_{ox} is the thickness of the oxide layer. Here the EHTC is a function of the HTC on the oxide-free surface, the thickness of the oxide layer, and the thermal conductivity of the oxide layer:

$$h_{eff} = \frac{q_s}{T_s - T_\infty} = \frac{q_s}{(T_s - T_p) + (T_p - T_\infty)} = \frac{q_s}{q_p\frac{\delta_{ox}}{\lambda_{ox}} + \frac{q_p}{h}} \approx \left(\frac{\delta_{ox}}{\lambda_{ox}} + \frac{1}{h}\right)^{-1} \tag{5}$$

where h_{eff} is a function of T_s and h is a function of T_p. If we know the thickness of the oxide layer (δ_{ox}), the thermal conductivity of the oxide layer (λ_{ox}) and the HTC on the oxide-free surface (h) at temperature T_P, we can roughly evaluate h_{eff} at the temperature between the steel and oxide layer (T_s). The temperature between the steel and oxide layer (T_s) can be obtained using Eqs. (2) and (4):

$$h(T_p - T_\infty) \approx \frac{\lambda_{ox}}{\delta_{ox}}(T_s - T_p). \tag{6}$$

Since the oxide layer is very thin compared to the thickness of the substrate, the heat accumulated in the oxide layer can be ignored. We then can obtain the temperature between the steel and oxide layer (T_s) as

$$T_s = T_p + \frac{\delta_{ox} h(T_p - T_\infty)}{\lambda_{ox}}. \tag{7}$$

Since Eq. (7) is valid for all temperature ranges, it can also be used to evaluate the effective Leidenfrost temperature, (T_{L_eff}), which is used to account for the influence of the oxide layer:

$$T_{L\_eff} = T_L + \frac{\delta_{ox} h_{min}(T_L - T_\infty)}{\lambda_{ox}}, \tag{8}$$

where h_{min} ($h_{min} = q_{min}/(T_L - T_\infty)$) is the HTC on the oxide free surface at the Leidenfrost temperature (T_L).

The above formulation can be used to compare with the experimental data presented by two papers dealing with spray cooling of oxidized samples [17,19]. The effective Leidenfrost temperatures presented in these papers were obtained for oxide layers formed on AISI 1008 [17] and on MS1200 [19] steels using nozzles with a water impingement density of 3.8 kg m^{-2} s^{-1} in cooling