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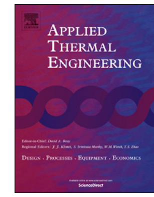

Enhancement of heat transfer rate in air-atomized spray cooling of a hot steel plate by using an aqueous solution of non-ionic surfactant and ethanol

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HIGHLIGHTS

- Air-atomized water spray cooling of a very high temperature surface was investigated.
- Surfactant and ethanol additives promoted the transition and nucleate boiling heat transfer rates.
- Critical heat flux value increased by using additives in pure water coolant.
- Additives in coolant enhanced the cooling rate up to 235 °C/s for ROT application.
- The obtained cooling rates were found to be in the higher range of an UFC.

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ABSTRACT

Air-atomized spray cooling, where compressed air atomizes water into fine droplets, is an efficient alternative to conventional cooling techniques. The present work deals with the air-atomized spray cooling of a 6 mm thick stainless steel plate having an initial surface temperature of 900 °C, using surfactant Tween 20 and ethanol additives. The main difficulty in achieving a high cooling rate at elevated surface temperatures is the Leidenfrost phenomenon. The metallurgical properties of steel are highly affected by the run-out table cooling rate between the temperature range of 900–600 °C. Another important cooling region, particularly to achieve the high strength martensite microstructure in steel, is 900 °C–200 °C. Therefore, in this study, the heat transfer studies have been done over those temperature regions. The physical properties of the coolant mixture were measured to understand the heat transfer enhancement mechanism. The results show that increasing the ethanol fraction in pure water (with or without surfactant) enhances the critical heat flux, heat transfer coefficient and cooling rate of a hot surface in the nucleate and transition boiling regimes. A maximum cooling rate of 183 °C/s has been obtained with the ethanol–water mixture; whereas ethanol–water–surfactant mixture gives a cooling rate of 235 °C/s, both of which lie in 'ultrafast cooling' regime.

1. Introduction

Enhancement of heat removal from a hot surface is an important criterion in steel industries to control the mechanical properties of strips/plates being cooled. In steel industries, the strips are rolled at a temperature of 900 °C or above in a typical Hot Strip Mill. Then they are cooled down to a coiling temperature of 600 °C in a run-out table (ROT) [1]. This is the most important temperature regime for the metallurgical phase transformations in steel and the cooling rate in this temperature range plays an important role. Higher heat transfer rate results in more improved mechanical properties due to the formation of multi-phase microstructures such as ferrite–martensite, ferrite–bainite or a mixture of bainite, martensite and residual austenite etc., in steel. Moreover, to study the transformation of steel into martensite phase microstructure, the heat transfer rate between 900 and 200 °C is also relatively important. The steel containing martensite microstructure is an important prerequisite for many high strength applications. The fully martensitic microstructure, resulting from very high cooling rate in the temperature range of 900–200 °C, offers the ultra high strength in steel [2]. In general, water is used as a heat transfer fluid to cool the steel, and is impinged on the surface in a number of ways such

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as jet, spray, air-atomized spray, etc. The conventional laminar water jet cooling is usually fitted with the ROT of a rolling mill. However, the impingement of water is limited to stagnation point which results in lesser heat transfer area; therefore, the overall heat removal rate from the surface decreases [3–7]. Spray cooling, in which water droplets impinge on the surface such that the surface area occupied by each droplet increases, is one such technique to maximize the heat transfer area [8–10]. The difficulty in achieving a higher heat transfer rate at high surface temperatures in water spray cooling is explained by the Leidenfrost phenomena [11]. The Leidenfrost effect [12] is a phenomenon, in which, due to excessive temperature difference between the liquid and solid phases, a thin vapor layer forms between the heated surface and the droplet upon impingement which prevents the droplet to wet the solid surface. Due to this, at the initiation of cooling a sudden vapor layer appears on the surface over which the spray droplets float. As a result, film/transition boiling heat transfer occurs, which results in poor heat removal rate as the test surface is covered by the vapor film. Hence, it is essential to consider a cooling system which can enhance the heat transfer rate by controlling the aforementioned problems, and one such type is air assisted water spray cooling [13,14]. Here, the water is atomized into fine droplets using compressed air and sprayed on to the surface to be cooled. The advantages of atomized spray cooling over other techniques are: 1) atomized spray produces uniform cooling as compared to others; 2) in atomized spray, high volumetric flow of air sweeps the partially evaporated droplets to avoid the accumulation of water droplets; 3) at higher surface temperatures, the heat transfer rate in an atomized spray cooling is higher than the conventional jet or spray cooling. Furthermore, this has been found to be an efficient cooling system to attain an ultrafast cooling rate [15,16]. The achieved cooling rate is said to be in the ultrafast regime when the product of the cooling rate (°C/s) and the plate thickness (mm) exceeds a value of 800. Thus the high heat transfer capabilities of an air-atomized spray cooling further augment the interest to investigate the enhancement of ultrafast cooling rate, which is important in ROT cooling in steel industries to form the multiphase microstructures [17,18].

Researchers have worked upon the enhancement of heat transfer rate in pure substances using additives such as oils, nano particles, salts, surfactants and alcohols and so on [19–27]. The main idea of using additives is to enhance the spreading and the evaporation rate of impinged spray on the solid surface by altering the physical properties of coolants [28]. Gadreck et al. [20] found that the heat transfer rate of nickel disk is enhanced by an oil-in-water emulsion jet. It is also reported that the decrease in surface tension causes an increasing number of bubble nucleation sites by minimizing the critical radius. Several authors have used the surface active agents to enhance the wetting/spreading capacity of coolant on the surface so that the heat removal rate increases [29,30]. Chandra et al. [31] found that the enhancement of spray cooling heat transfer rate occurs by the addition of anionic surfactant such as sodium dodecyl sulfate. It was observed that a decrease in the contact angle between the spray droplets and the solid surface increases the heat transfer rate by promoting the spreadability, as a result of which the evaporation rate of droplets becomes high. Moreover, the enhancement of evaporation rate by decreasing the contact angle has also been pointed out by Picknett and Bexon [32] and Bourges-Monnier and Shanahan [33]. Similarly, Clay and Miksis [34] found that a decrease in surface tension causes a decrease in contact angle, as a result of which the droplet motion increases. The advantages of the addition of surfactant to water during spray cooling of copper surface have been explored by Jia and Qiu [28]. It has been revealed that there are two advantages with surfactant water, namely stable critical heat flux and lower super heat temperatures. Tinker et al. [26] investigated the effect of surfactant on drop-wise evaporative cooling. It was observed that the liquid surface tension and contact angle decrease with the addition of surfactant, which results in the spreading of the droplet on the surface. This causes the droplet evaporation to start at a faster rate. Recently, the advantages of using surfactant water in an air atomized spray for the enhancement of heat transfer rate of a high temperature (900 °C) stainless steel plate have been demonstrated by Mohapatra et al. [35]. In addition to this, the enhancement of heat transfer rate of hot surface during surfactant water jet impingement cooling was also studied [36]. The surfactant used was an anionic surfactant (sodium dodecyl sulfate). The major focus of their research was to increase the cooling rate of a stainless steel plate, especially for application in the ROT cooling, at different surfactant concentrations varying from 0 to 1000 ppm. It was found that an increase in surfactant concentration increases the cooling rate up to an optimal surfactant concentration (600 ppm); thereafter it decreases due to the effect of excessive foaming. Cheng et al. [37] compared the effects of adding high-alcohol surfactant (HAS, i.e. 1-octanol or 2-ethyl-hexanol) and salt additives (NaCl or Na_2SO_4) to spray cooling, and found that HAS, especially 2-ethylhexanol, shows a higher rate of heat removal. This is due to the fact that HAS lowers the surface tension of the working fluid, leading to the droplet-film impaction.

In open literature, several studies have been performed to understand the effect of alcohol/water mixture, with or without surfactant, on the enhancement of heat transfer rate; however, the studies have been restricted to pool boiling heat transfer. For example, Inoue et al. [22] reported that the heat transfer rate is enhanced by the addition of ethanol and surfactant to water. The heat transfer rate of the binary mixture is high compared to that of pure substances. It was reported that the number of boiling nucleation sites on the surface increases with an increase in surfactant and ethanol concentrations in water. Shoji and Nishiguchi [24] measured the critical heat flux in a binary mixture of butanol and water. They concluded that the critical heat flux of water is enhanced by adding small amounts of butanol, due to the generation of numerous tiny bubbles and their degree of coalescence. This generation of tiny bubbles increases with an increase in concentration density of butanol.

Therefore, from the above literature it is found that surface tension, contact angle and evaporation rate of droplets play a promising role in the enhancement of heat transfer rate for various heat transfer or cooling applications. The above factors motivate the research and necessitate a more detailed study on the heat transfer during air-atomized spray cooling with a mixture of ethanol and water in the presence of a surface active agent. The application of these mixtures for the enhancement of spray impingement boiling and the study of heat transfer aspects during cooling is an important area of research, particularly in the ROT of a steel industry.

In the current study, the effect of alcohol concentration on surface tension and contact angle has been primarily examined with pure water and water with surfactant as a fundamental research on the heat transfer enhancement. Secondly, air-atomized spray cooling of a hot stainless steel plate has been done with alcohol/water mixtures, with or without the presence of surfactant, to measure the surface cooling rate, heat flux and heat transfer coefficient. The range of ethanol fraction considered in the experimental study varies between 0 and 700 ppm (0.013–0.089 vol%), and the surfactant used is polysorbate 20 (Tween 20) at 56 ppm. The reason behind the selection of a non-ionic surfactant of specified concentration is that it induces less foaming, and its effect on the surface tension and contact angle is more pronounced at this concentration. Moreover, in order to achieve heat transfer enhancement, an optimum surfactant concentration is needed as it is dependent on the Marangoni number ($Mg = \Delta\sigma d/\mu k$, where σ is