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Experimental investigation of air-atomized spray with aqueous polymer additive for high heat flux applications

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ABSTRACT

The experimental investigation of using a water based polymer additive to enhance the spray cooling performance of hot steel plate, has been carried out in the current research. This is essentially important to produce high-strength steel on the run-out table (ROT) of a Hot Strip Mill. The ultra-high heat flux cooling system has been developed using an air-atomized spray, containing dissolved polyvinylpyrrolidone (PVP) in water at different concentration ranges between 10 and 150 ppm and compared with the cooling performance of pure water. To understand the heat transfer mechanism of aqueous polymer solutions, the physical properties such as surface tension, viscosity and thermal conductivity were measured. The cooling experiments were conducted using an AISI 304 stainless steel plate of 6 mm thickness initially kept at a temperature above 900 °C, where the Leidenfrost effect is predominant. In these experiments, the transient temperature data during cooling has been measured with three subsurface thermocouples and this time-temperature history has been used to estimate the surface temperature and the surface heat flux histories using a commercial inverse heat conduction software namely, INTEMP. The results explain that the polymer solution has a significant effect on the enhancement of surface heat flux, critical heat flux, as well as the cooling rate of the test plate. It was observed that an increase in the polymer concentration increases the heat transfer rate up to an optimal concentration; after which it results in a reduction in the rate. A maximum cooling rate of 253 °C/s was obtained with a critical heat flux of 4.212 MW/m^2, which can be termed as the higher range of an 'Ultrafast cooling' process. Overall, the aqueous polymer solution can serve as a better heat transfer fluid for high heat flux applications.

1. Introduction

Atomized spray cooling is an important technique that can be used for high heat flux applications starting from electronics, nuclear fuel rods, space systems, and various metal quenching processes. This method can also be an alternative to conventional laminar jet impingement cooling in the run-out table (ROT) of a Hot Strip Mill (HSM) in steel processing plant. The mechanical properties of the steel strip is conditioned and altered only negligibly in the hot rolling mill of steel industries. However these properties can be greatly modified by controlling the cooling rate of steel between a temperature range of 900–600 °C [1,2]. Steel for high-strength applications necessitates multiphase microstructures such as ferrite–bainite, ferrite–martensite and pearlite–martensite, etc. [3,4], which can be processed by applying cooling rates greater than 150 °C/s. The conventional means of laminar cooling technology equipped with ROT cannot provide these multiphase microstructures, because the acquired cooling rate is limited to a lower extent, usually in the range of 30–80 °C/s. Moreover, jet impingement cooling can be adversely influenced by film boiling, and the heat transfer rate is limited to the stagnation point, which causes unacceptable distortion and high residual stresses. Although the water spray cooling can provide higher cooling rates, it encounters the Leidenfrost phenomenon [5–7]. Due to this a layer of vapor film builds up on the hot surface as a result of a high thermal gradient between the solid and liquid phases, which restricts the opportunity of solid–liquid contact resulting a low heat transfer rate at high surface temperatures [8]. Under such circumstances, air-atomized spray cooling appears to be a promising alternative for ROT applications. Here, compressed air used for atomization sweeps the partially evaporated droplets from the surface, which results in the breakdown of the vapor film and the high momentum droplets gained by a higher value of air pressure can touch the hot surface; therefore, the film boiling heat transfer greatly reduces [9–11]. Since the temperature of the plate is much higher than the coolant temperature, the current system falls under high heat flux application where different boiling heat transfer regimes exist during the cooling. The characteristic heat transfer mechanisms associated with the air-atomized spray cooling of

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Nomenclature

B	strip thickness, mm
C_p	specific heat, J/kg K
d_0	orifice diameter, m
k	thermal conductivity, W/m K
L	strip length, mm
t	time, s
T	temperature, °C
x	direction along the length of the plate, mm
y	direction along the thickness of the plate, mm
U_A	velocity of air, m/s

Greek symbols

θ	contact angle, deg
ρ	density, g/cc
σ	surface tension, mN/m
λ	wave length, cm
μ	viscosity, mPa s

Abbreviations

AFR	air–fluid ratio
CHF	critical heat flux, MW/m^2
CPC	critical polymer concentration, ppm
PVP	polyvinylpyrrolidone
ROT	run-out table
SMD	sauter mean diameter, µm
T/C	thermocouple
UFC	ultrafast cooling

high temperature steel plates are transition boiling at high surface temperatures, nucleate boiling heat transfer and finally single phase forced convection at low surface temperatures [12]. Moreover, on the other hand, no film boiling heat transfer exists in air-atomized spray cooling which was the dominant factor in the case of jet impingement cooling [11]. In order to create the desired cooling rate for a particular application, it is essentially important to control the phenomena of boiling heat transfer during the cooling process. Therefore, it is an area of overwhelming pragmatic significance as well as of considerable fundamental importance. The experimental approach employed in the present research can serve to control the high heat flux systems existing in various industries.

Considerable experimental and theoretical work on the cooling of a hot metal plate using different processes such as jet, spray, air-atomized spray, etc., have been carried out by different researchers [13–18]. However, only a few studies have reported the cooling performance of an air-atomized spray impingement on a high-temperature metal surface in conjunction with an inverse heat conduction technique to estimate the surface boiling characteristics. For example, De Oliveira et al. [13] reported the air-atomized spray cooling of an AISI 304 stainless steel plate over a wide range of water flow rates and at an initial surface temperatures up to 850 °C. They found that heat transfer coefficient is strongly dependent on those variables. They also concluded that air-atomized spray cooling has an advantage over conventional water sprays as it is able to achieve higher heat transfer coefficients under similar operating conditions. They used the commercial inverse heat conduction solver, namely INTEMP to estimate the surface temperature and heat flux values using the measured internal temperature data by the thermocouples. Al-Ahmadi and Yao [19] studied the effect of water mass flux and air pressure for an air-mist spray, cooling a stainless steel plate initially kept at 900 °C. They concluded that water mass flux has a greater effect on the heat transfer rate than air pressure. From the investigation of [11], it was observed that water mass flux is an important parameter in atomized spray cooling for a metal surface of temperature 600 °C. Bhattacharya et al. [20] presented a theoretical analysis of spray evaporative cooling to achieve higher heat transfer rates in terms of the size of water droplets impinging on the hot surface. It was reported that droplets of lower size have a higher heat transfer capability due to rapid evaporation from the hot surface.

The boiling heat transfer behavior of the coolant fluid (water) is highly influenced by its thermo-physical properties [21]; several works are reported in the literature for additive based heat transfer enhancement in different cooling processes [22–26]. However, some studies are limited to pool boiling heat transfer [27–30]. Recently, the enhancement of heat transfer rate in jet and air-atomized spray impingement cooling of hot metal surfaces with dissolved surface active agents in pure water have been carried out by the authors [25,31,32]. There exists an optimal solution concentration of surfactant for higher heat transfer enhancement. A maximum cooling rate of 214 °C/s has been achieved with AISI 304 stainless steel (initial temperature 900 °C) using non-ionic surfactant added air-atomized water spray [33]. It is concluded that addition of surfactant decreases the surface tension and hence higher wettability of the surface occurs with minimal solid–liquid contact angle, which increases the heat removal rate from the surface. However, foamability of the surfactant type and its concentration also play a key role in the motion of wetting fronts on the hot surface. Moreover, the influence of viscosity of coolant on the heat transfer rate while working with surfactant added water was also explored in detail. The results are in substantial agreement with those from the previous studies [26,29,34–37]. Apart from using surfactants, studies have also been conducted using polymeric additives on the enhancement of heat transfer [37]. Kotchaphakdee and Williams [38] did the pioneering work identifying the pool boiling heat transfer enhancement with different polymeric additives in water. They reported that surface tension alone is not the dominant factor in heat transfer enhancement, whereas, molecular weight and the concentration of the polymer, and the viscosity of the solution also play a crucial role. Therefore, it is important to understand the effect of polymer additives on the physical properties of the coolant for heat transfer enhancement. In general, most polymeric solutions do not show significant effect on surface tension; whereas polymer of higher concentrations dissolved in water cause a significant increase in viscosity. However, some water-soluble polymers like hydroxyethyl cellulose (HEC) and polyvinylpyrrolidone (PVP) decrease the surface tension with increasing concentration similar to that of surfactants [38–40]. Zhang and Manglik [41] experimentally studied the decrease in surface tension of water by HEC polymeric additive. Similar to the critical micelle concentration of surfactant, a critical polymer concentration is also relevant in polymeric surfactant additive solutions.

It must be pointed out from the literature that selection of a polymeric additive that can serve like a surfactant is better for heat transfer enhancement when working with polymeric additive solutions. Moreover, working at low concentration of polymers is advantageous for heat transfer enhancement as non-Newtonian fluidic shear-thinning behavior will arise at high concentrations. It is also found from the literature that polymeric additives of lower concentration enhance the nucleate boiling heat transfer rate. However, most of the previously published work on polymeric