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Ultrafast cooling processes with surfactant additive for hot moving steel plate

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ABSTRACT

The study of ultrafast cooling of a hot moving surface is very important, as it is applicable in many industries, such as cooling of a hot steel strip on the run out table in steel industry. In general, the run out table is fitted with laminar water jets where the achieved cooling rate is very less because of the Leidenfrost phenomenon. The current research is focused on the comparative study of the cooling processes; by using water jet and air atomized spray cooling techniques on the hot stationary and moving surface. The coolant used in both the cases is surfactant added water with varying concentration of surfactants. In case of stationary bed, the maximum cooling rates achieved for both jet and air atomized spray cooling are at a surfactant concentration of 225 ppm, the values being 167 and 224 °C/s, respectively. On the contrary, for moving surface, highest cooling rates of 163 and 127 °C/s are obtained at a low surfactant concentration of 75 ppm for jet and spray cooling respectively. It is interesting to observe that addition of surfactant has a negative effect on cooling rate for a hot moving surface.

1. Introduction

The jet impingement and air atomized spray cooling techniques are efficient in attaining ultrafast cooling rate on high temperature steel plate [1–3]. These cooling techniques can be applicable for many industrial processes such as for gas turbine blades, laser/-plasma cutting and high power electronic chips. In addition, the steel industries have also adopted the jet impingement cooling technique at the run-out table to produce high cooling rates [4]. The cooling effectiveness of a hot moving surface strongly depends on the coolant properties and the impingement technique. The coolant impingement technique is important because in the traditional laminar jet and spray impingement techniques the chances of film boiling is more [2] whereas, in the air atomized spray cooling the heat transfer rate is high due to the absence of film boiling [5,6].

Generally, in the metallurgical industries, laminar water jet and water spray are used for the cooling of hot metallic parts. In these cooling techniques the vapor layer formed between the hot surface and liquid causes drastic decrease in heat transfer rate and the process is known as film boiling [7,8]. This phenomenon of formation of a vapor film between the solid and liquid interface is called as the Leidenfrost effect. Therefore, it is very difficult to achieve an ultrafast cooling (UFC) rate in the laminar jet and traditional spray impingement cooling processes. Ultrafast cooling rate is attained when the product of the cooling rate (°C/s) and the plate thickness (mm) goes beyond 800 [9]. In the run-out table cooling, the cooling rate is defined as the slope of the temperature-time curve taken over the specified temperature interval of 900–600 °C. This temperature range is important because of occurrence of metallurgical phase transformation in steel [10].

Extensive literature is available on the cooling behavior of hot stationary steel plate by using water jet and spray cooling techniques [8,11–14]. An analytical approach of a jet impingement boiling heat transfer was presented by Timm et al. [15] where it was reported that the film boiling has been associated at the stagnation region of an impinging jet. Wang et al. [11] used the water jet impingement on a hot stationary steel plate to investigate the heat transfer phenomenon, and reported that, heat transfer coefficient has non linear variation with surface temperature and is not affected by water flow rate in the range of 15–35 l/min. The effects of nozzle inclination and water flow rate on the cooling rate of a hot plate were studied by Ravikumar et al. [3] and Chester et al. [16]. They reported that water flow rate and nozzle inclination have significant effect on the cooling rate. Jet impingement cooling of a hot stationary steel plate was studied by Ravikumar et al. [4] and it was reported that the highest cooling rate was found at 400 mm nozzle height. Chen et al. [17] studied the cooling

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Nomenclature

C_p	specific heat capacity (J Kg^{-1} K^{-1})
h	heat transfer coefficient (W m^{-2} K^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
q	surface heat flux (MW/m^2)
T	surface temperature (°C)
T_f	coolant temperature (°C)
TC1	thermocouple one
TC2	thermocouple two
TC3	thermocouple three
T_i	initial surface temperature (°C)
X	direction along the length of the plate (mm)
Y	direction along the thickness of the plate (mm)

Greek

μ	viscosity (cP)
ρ	density of the steel plate (kg m^{-3})
α	thermal diffusivity (m^2/s)
Δt	time interval required to cool the plate from 900 to 600 °C (s)

Abbreviations

CHF	critical heat flux
HTC	heat transfer coefficient

mechanism of hot stationary and moving steel plate and reported that heat transfer rate has been enhanced in the downstream of stagnation point due to plate motion. Chattopadhyay and Saha [18] used the slot jet impingement on the hot moving steel plate and observed that while increasing the plate velocity, the Nusselt number distribution becomes uniform. Nasr et al. [19] also reported that the surface heat removal rate is reduced due to increasing velocity and it is shifted to downstream with respect to spray centreline, however they used the rotating disk for cooling surface. Zumbrunnen [20] found the five cooling zones by using jet nozzle and it was reported that the maximum heat flux is in the stagnant zone. Pohanka et al. [21] studied the heat transfer from the moving surface by spray impingement and reported that the heat transfer coefficient increases with decreasing surface temperature. Franco et al. [22] made an experimental study to cool the hot moving steel plate by using the multiple top jet nozzles and reported that the heat transfer capability is more with wider spaced jet. From the existing literature it is clear that the cooling of stationary metal surface is studied by numerous researchers, but few studies are available on the cooling behavior of a hot moving steel surface. In many metallurgical industries, hot moving surfaces are involved which must be cooled to get the phase transformation, as for example run out table cooling in the steel industry. Therefore, the current research has been motivated to study the cooling behavior of a hot moving steel plate because of its wide applications. The study on the cooling of hot moving surfaces with pure water jet and spray can also be found in the open literature but none of the researchers have reported ultrafast cooling rate. While for the stationary surface some of the investigators have reported that the aqueous surfactant additives in the coolant produce the ultrafast cooling rate [6,9]. Therefore, in the current research the aqueous solution of surfactant cetyltrimethyl ammonium bromide (CTAB) has been used as a coolant.

The addition of surfactant reduces the surface tension of water as well as the contact angle between droplet and steel surface [9]. Due to the reduction in contact angle, the spreadability of the droplet on the steel surface increases and consequently the droplet thickness decreases [23]. As the droplet spreads more on the solid surface, the contact area increases and therefore the droplet evaporation rate is faster [24]. Ravikumar et al. [3] studied the effect of spray (pure water and with aqueous solution of surfactant) inclination on the ultrafast cooling rate and found that on increasing the spray inclination angle the surfactant added water decreases the cooling rate whereas in the case of pure water spray, the cooling rate first increases and then gradually falls. Qiao and Chandra [24] studied the boiling phenomena of surfactant added water droplet on the hot (temperature limited to 340 °C) steel surface. They reported that only in the nucleate boiling regime the surfactant added water spray enhanced the cooling efficiency. The heat transfer rate had also been enhanced by the binary mixture of two different kinds of surfactant solution [25,26]. From the open literature it is found that the surfactant additives enhance the heat transfer rate; however the study is limited for a stationary steel plate only.

Therefore, the current investigation deals with the heat transfer study of a hot moving surface by jet and air atomized spray impingement with aqueous solution of surfactant CTAB as a coolant. It is a cationic type of surfactant having chemical formula ($C_{16}H_{33}$) N (CH_3)$_3$Br and the positive charge appears on nitrogen atom. The critical micelle concentration of this particular surfactant is 325 ppm which has been reported by Ravikumar et al. [9]. In the present investigation the concentration of the surfactant has been varied in four levels which have been described in the later experimental design section.

2. Experimental details

2.1. Experimental apparatus

The experiments are conducted on an indigenously designed and fabricated moving bed experimental setup as shown in Fig. 1. It consists of a motor, pulley, shaft, crank, connecting rod and slider. A motor (3HP) drives a pulley and the crank is connected to the pulley through a shaft. The motor rpm is controlled by ABB drive (ACS350-03E-05A6-4); thus the speed of the moving bed is controlled. The connecting rod joins the crank and slider, such that, the circular motion of the crank is converted into reciprocating motion of slider. The movement of the slider is restricted to 0.1 m in the forward direction then it comes back in the opposite direction for 0.1 m which induces a reciprocating motion. Two different impingement techniques have been applied on the hot moving steel plate namely jet and air atomized spray. In the jet cooling process, the nozzle has been fixed at 400 mm above from a stationary plate surface which is the optimum height obtained by Ravikumar et al. [4] whereas, in the air atomized spray cooling the distance between nozzle tip and plate surface is kept at 60 mm as on this height the cooling rate obtained is in the range of ultrafast cooling as reported by Ravikumar et al. [9]. The top surface of the plate has been exposed by coolants in all the experiments and all other surfaces are covered by ceramic brick. The water and air rotameters have been used to measure the coolant and air flow rate, respectively. In between the rotameter and nozzle, solenoid valves are arranged for sudden release of water and air on the impingement surface.

The cooling experiments have been conducted on the hot steel plate of dimensions 100 mm × 100 mm × 6 mm. The schematic diagram of the steel plate with the thermocouple location has been