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Thermal Characteristics of Air-Water Spray Impingement Cooling of Hot Metallic Surface under Controlled Parametric Conditions

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Experimental results on the thermal characteristics of air-water spray impingement cooling of hot metallic surface are presented and discussed in this paper. The controlling input parameters investigated were the combined air and water pressures, plate thickness, water flow rate, nozzle height from the target surface and initial temperature of the hot surface. The effects of these input parameters on the important thermal characteristics such as heat transfer rate, heat transfer coefficient and wetting front movement were measured and examined. Hot flat plate samples of mild steel with dimension 120 mm in length, 120 mm breadth and thickness of 4 mm, 6 mm, and 8 mm respectively were tested. The air assisted water spray was found to be an effective cooling media and method to achieve very high heat transfer rate from the surface. Higher heat transfer rate and heat transfer coefficients were obtained for the lesser i.e, 4 mm thick plates. Increase in the nozzle height reduced the heat transfer efficiency of spray cooling. At an inlet water pressure of 4 bar and air pressure of 3 bar, maximum cooling rates 670°C/s and average cooling rate of 305.23°C/s were achieved for a temperature of 850°C of the steel plate.

Keywords: air-water spray, transient temperature, cooling rate, plate thickness

Introduction

The thermo-metallurgical properties change of steel take place during runout table (ROT) cooling and this methodology unavoidably manages the mechanical natures of the material being handled. In a typical ROT process the stripes of steel are heated until they reach to a temperature of 900°C and advanced into roughing and completing plants after which the temperature is brought down to 600°C [1]. In such a way, by cooling in this temperature cover a mixture of different microstructures (pearlite-martensite, ferrite-martensite or martensite alone) must be created to create propelled high quality steels. Alloying up with components like chromium, manganese, molybdenum are essential to create the complex microstructures. It is extremely hard to create microstructures within this short time by using conventional laminar cooling technology on ROT. In fact these microstructures are controlled by high cooling rates. As the creation of microstructure is accompanied with aggressively fast cooling, laminar cooling is not an efficient option hence evaporative cooling such as spray cooling seems to be helpful in producing steel of high quality coupled with all the necessary attributes. Some of the earlier researchers [2-6] studied the implementation of the ultra-fast cooling process. Researchers [7-12] determined maximum cooling rates of 424.2°C/s, 502.81°C/s and 573.1°C/s attained for wall super heat ΔT = 600°C, 700°C and 800°C respectively for inlet pressure of 0.8 Mpa while studying the effects of the properties of spray on the cooling time and rate under varying inlet pressure when water was used as a coolant. Somasundaram and Tay [13] proposed that full cone nozzles which can spray uniformly at lower flow rates are more suitable for intermittent spray cooling,

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enhancing the efficiency while conducting a test using commercial nozzle attached to a solenoid valve. Hou et al. [14] measured the critical heat flux (CHF), heat transfer coefficient, cooling surface temperature within the nozzle inlet pressure domain of 0.6-1.0 MPa.

The thermal characteristics of air-water spray impingement cooling of hot metallic surface are investigated and reported in this paper. The controlling input parameters considered were the combined air and water pressures, plate thickness, water flow rate, nozzle height from the target surface and initial temperature of the hot surface. The effects of these input parameters on the important thermal characteristics such as heat transfer rate, heat transfer coefficient and wetting front movement were examined. Hot flat plate samples of mild steel with dimension 120 mm in length, 120 mm breadth and thickness of 4 mm, 6 mm, and 8 mm respectively were tested.

Experimental setup and procedure

A schematic ultrafast cooling setup is shown in Figure 1.

The main components of the setup were a water delivery system, spray generator, a heating system and instrumentation. The water delivery system consisted of a 500 litres overhead tank attached with a positive displacement pump, solenoid valve, pressure regulator, flow meter and pressure gauge. Deionised water was used as coolant in the experimentation. The spray generator was a commercial atomizer (supplied by Spraying System Co, Bangalore, India). The spray generator comprised of an internally mix air atomized nozzle. The generator allowed air from a compressor and water from the tank. Air and water were passed through solenoid valves separately. Air assisted water flow rate was controlled by regulating the inlet pressures. The spray generator was operated by the help of a sophisticated electronic control panel. With the fine adjustment of shaping air pressure, round shaped full-cone sprays with angles between 19° and 22° were obtained. Air supply pressures used for the atomization of water were varied from 2 bar to 4 bar. The open electrical heating technique [15] was adopted for heating the test samples to maintain high surface temperature above Leidenfrost temperature, so that the tests could be carried out in the film boiling regime. The instruments used in the setup consisted of (1) the K-type thermocouples embedded at the bottom surface of the plate at different desired locations by spot welding as shown in Figure 2(a) and the thermocouple location is depicted in Figure 2(b) and (2) a data acquisition system (CHINO, model: KR2000) supported with application software ZAILA. A test stand was designed and fabricated to accommodate the cooling mechanism which was 7 ft height and consisted of a rectangular test bed of dimension 250 mm × 200 mm on which the test plate was placed during experimentation.

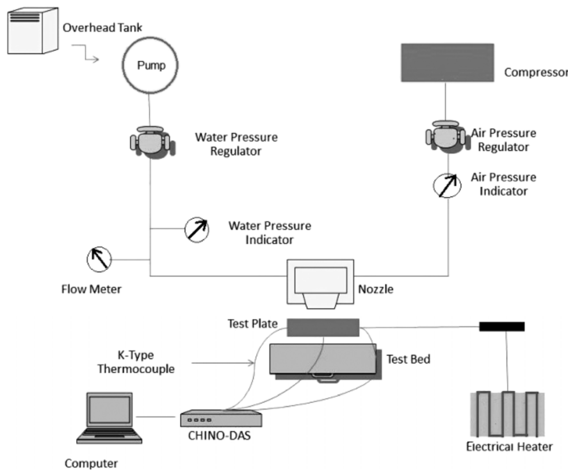

Fig.1 Schematic of the spray cooling setup

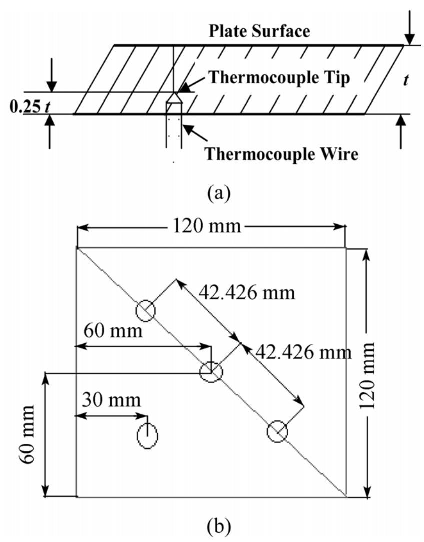

Fig. 2 (a) Thermocouple installation method and (b) Embedded thermocouple locations

During heating of the test samples, a temperature clearance of +100°C was kept so as to maintain the desired temperature at the time of manual shift from heater to the test bed. Before the start of spray, the air and water pressures were preset at desired values. Then the spray was impinged by turning on the spray system with the help of the control switches attached to the control panel. The tests were repeated for various combinations of water and air pressures. The ranges of water pressure and air pressure taken were from 0.0 bar to 4.0 bar. The water flow rate was recorded at each air water pressure combinations. The real time temperature data from each thermocouple was acquired by the help of CHINO data acquisition system and store in the computer loaded with the ZAILA application software. The tests were carried out at three different nozzle heights i.e, 120 mm, 180 mm, and 240 mm and three different plate thicknesses i.e, 4 mm, 6 mm and 8 mm respectively. From the recorded transient temperature data, the heat transfer rate and heat transfer coefficients from the surface were computed by using suitable empirical formulae.

Measurement of water flow rate

For each combination of air and water pressures, the water flow rate was recorded by using a rotameter attached with the spray system. To understand the contribution of both the fluids in the spray generation, the pressure and flow rate data were plotted as shown in Figure 3.

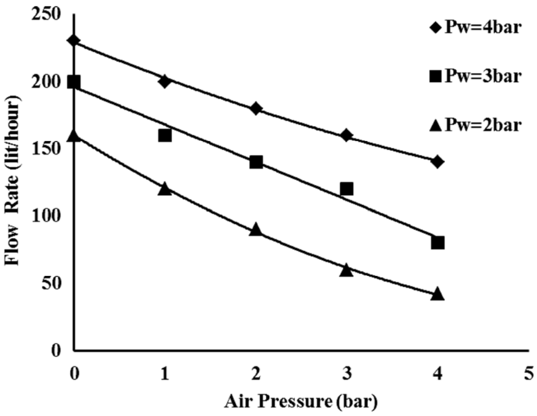

Fig. 3 Water flow rate versus air pressure

The flow rate profiles in Figure 3 reveals that air pressure has a dominant role in the spray generation process. The water flow rate decreased with increase in air pressure which was expected. The atomization intensity was increased with the increase in air interference.

Instrumental uncertainty

The K-type thermocouples used in the experimentation were having accuracy range of ± 2.1°C in the range of temperature measurement from −100°C to 1260°C. The operating conditions of the centrifugal pump used include: liquid temperature ranges from 0°C to + 90°C, ambient temperature up to + 55°C and maximum operating pressure from 0°C to + 40°C is up to 10 bars and from +41°C to + 90°C is up to 6 bars. The rated flow of the pump is 2.5 m^3/h. The rated head is 37.2 m. The maximum head of the pump is 56 m. The power input to the pump at P_1 is 820 W where as at P_2 it is 580 W. The nozzle water output was changed to various combinations of water pressure and air pressure to attain required flow rate of air-water mixture. For example liquid pressure at 3 bars and air pressure at 3.5 bars, the air and water mixture flow rate from one nozzle is 84 LPH.

The cooling curves

Figure 4 shows an illustration of the transient temperature profile for the governing input parameters at all the specified locations of the thermocouples TC1, TC2, TC3 and TC4 on the plate with initial surface temperature of 850°C.

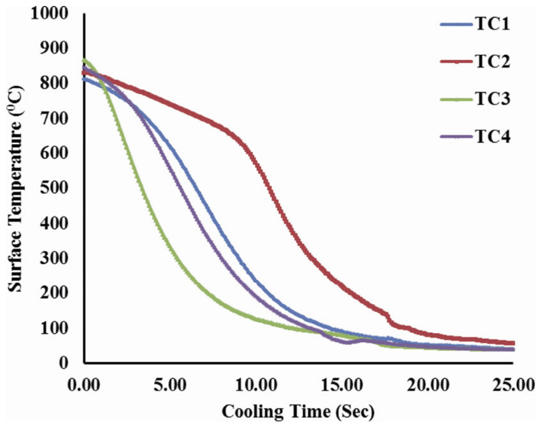

Fig. 4 Transient temperature profile (P_w = 4 bar, P_a = 4 bar, H = 240 mm and t = 6 mm)

Due to the open electric heating system, there might be higher temperature concentrated at the centrally located thermocouple TC3 compared to other three thermocouples, with a fluctuation of ± 50°C. The maximum cooling rates at the central thermocouples for 4 mm, 6 mm and 8 mm thick plates were computed as 305.23°C/sec, 98.02°C/sec, and 54.16°C/sec respectively from Figure 5.

The wetting front propagation

The wetting front as shown in Figure 6 moved from centre of the plate to the edges smoothly in the due course of time. The uniform spray distribution was achieved through the atomizing nozzle placed normal to the plate.

We confirmed the instance of surface wetting corresponded to the inflection in the cooling curve measured in the experiment. Therefore, the difference between the cooling curves at the four thermocouples was caused by the different times at which the surface-wetting phenomenon occurred.

During the experimentation a camera recorder (Sony) was used to record the wetting front propagation during spray impingement on the plate surface and the development of cooling. As the coolant hits the scorching surface, a dark spot is seen along the stagnation line which demonstrates a ultrahigh heat flux removal in that zone which brings about a huge temperature drop from the surface.

Cooling curves at different nozzle heights

Examples of the central cooling curves for the 4 mm thick plate at three different nozzle heights are presented

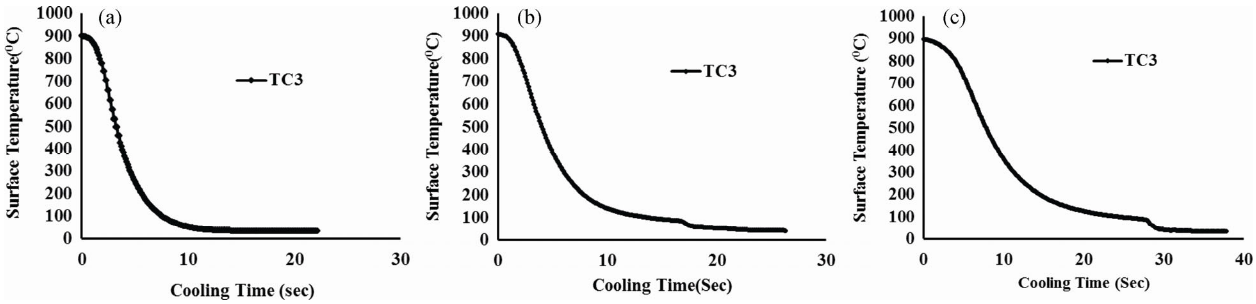

Fig. 5 Central thermocouple temperature profiles at 4 bar water pressure: (a) P_a = 3 bar, t = 4 mm, (b) P_a = 3 bar, t = 6 mm and (c) P_a = 3 bar, t = 8 mm

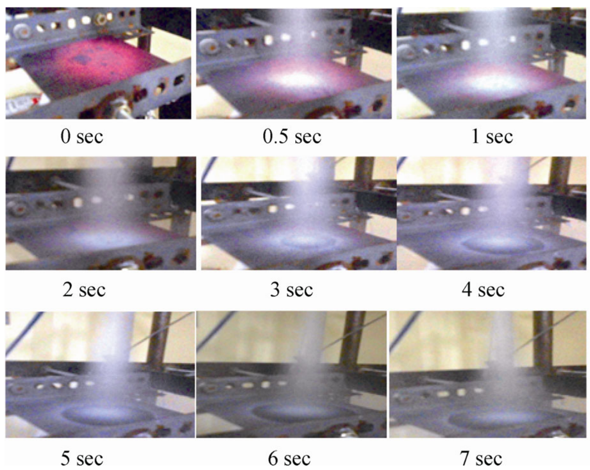

Fig. 6 Time dependent wetting front movement during spray cooling mechanism

in Figures 7-9. Figure 7 indicates that at nozzle height of 240 mm and lower air and water pressures of 3 bar each, the time of cooling was comparatively lesser than that for the cases of nozzle heights of 120 mm and 180 mm. But there is contradiction in the phenomena of dependency of nozzle height and inlet pressure with the trend of cooling curves, i.e, in both Figures 8 and 9, at 120 mm nozzle height and increased air-water pressures, the cooling time is comparatively less than that for the other two heights. This variation in results might be due to the fact that even though there is increase in spray cone angle with increase in nozzle height, at large air pressure, as the atomization is more, the finer water particles blown off from the plate surface. The results indicate that the role of inlet pressure was prominent as compared to the nozzle height for the higher thermal performance of the spray cooling.

The thermal characteristics

From the measured time dependent temperature data at each thermocouple location, the corresponding maximum value of cooling rates were computed by taking the peak values of temperature and time and using equation 1.

$$CR = \frac{T_2 - T_1}{\tau_2 - \tau_1}, \ ^\circ\text{C/sec} \quad (1)$$

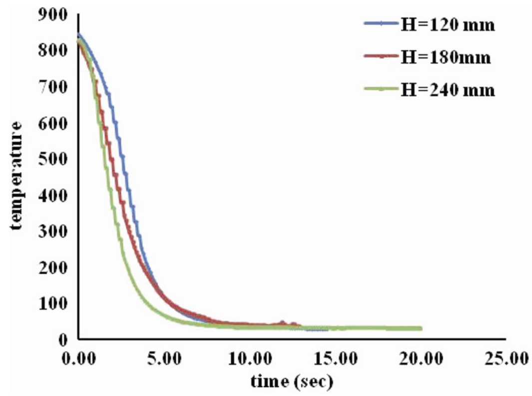

Fig. 7 Central thermocouple temperature profiles (P_w = 3 bar, P_a = 3 bar, t = 4 mm)

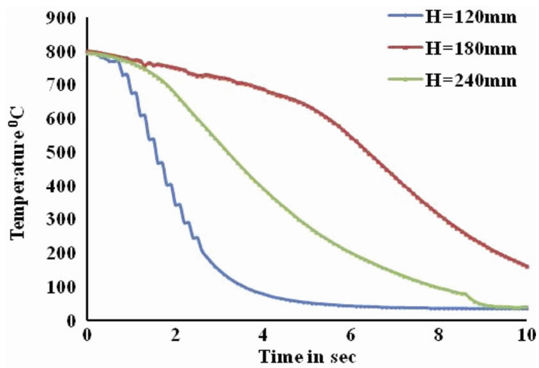

Fig. 8 Central thermocouple temperature profiles (P_w = 4 bar, P_a = 4 bar, t = 4 mm)

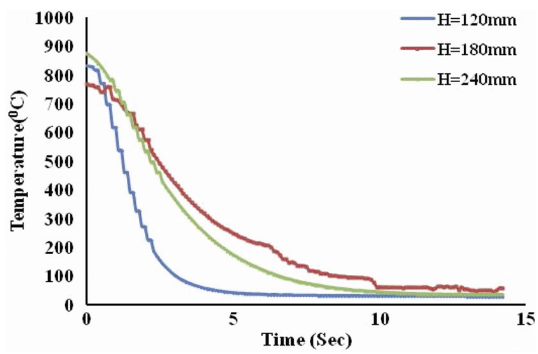

Fig. 9 Central thermocouple temperature profiles (P_w = 4 bar, P_a = 3 bar, t = 4 mm)

Where, CR is the maximum value of cooling rate (in °C/sec), T_2 = temperature (in °C) at the start of spray, τ_1 = real spray time (in sec) at the start of spray, T_1 = temperature (in °C) at the end of spray and τ_2= real spray time (in sec) at the end of spray.

The local heat transfer coefficients (HTC) from the plate surface were determined by using Equation 2.

From the energy equation:

$$h_c \times A \times \Delta T = m \times C_p \times \frac{\partial T}{\partial t}$$

where, $\Delta T = T_S - T_C$

$$m = \rho \times V = \rho \times A \times t$$

$$\frac{\partial T}{\partial t} = \text{Cooling Rate} = CR$$

$$h_c = (\rho \times C_p \times t \times CR)/(T_S - T_C) \quad (2)$$

where, h_c = heat transfer coefficient in W/m^2.°C, T_S= surface temperature in °C, T_C= coolant temperature in °C, ρ = density of mild steel in kg/m^3, C_p = specific heat of mild steel in J/kg.K, t = thickness of steel plate in mm.

Effect of air-water pressure combination

Figure 10 shows the cooling rates at different air pressures ranging from 0.0 bar to 4.0 bar. It could be observed that the highest value of cooling rate (CR) obtained for the central thermocouple at the 3 bar air and 4 bar water pressure combination, i.e., 305.23°C/sec. Experimental results reveal that the more is the air pressure, there is a significant change in the cooling rate at a fixed water pressure. Hence, mixing of air with water has a principal role in improving the heat transfer rate from the steel plate surface during spray quenching. These results help in optimising the controlling parameters for heat transfer expansion and ultra-fast cooling.

Effect of nozzle height

The variations of cooling rate at different pressure and with different nozzle height are reported in Figures 11.

Using the experimental procedure described above, cooling rates were measured at different combinations of air and water pressures for three nozzle height 120 mm, 180 mm, and 240 mm respectively. For the spray height, the influence is more complex as it could introduce different droplet flux distributions and impact energy on the test surface. As indicated, in Figure 11 (a and b) a general trend is watched that cooling rate reduces as the impinged spray height increases. But, in Figure 11 (b) most extreme cooling rate achieve for nozzle height 180 mm. In Fig. 11(c) at the cooling rate of 305.23°C/s, an optimal impinged spray height is found at 120 mm to achieve the maximum heat transfer coefficient. It is proposed that, as the impinged spray height increase from 120 mm to 240 mm, the droplets impact energy decreases, which disables the positive effect of the increased impinged cooling area and accordingly decreases the heat transfer coefficient.

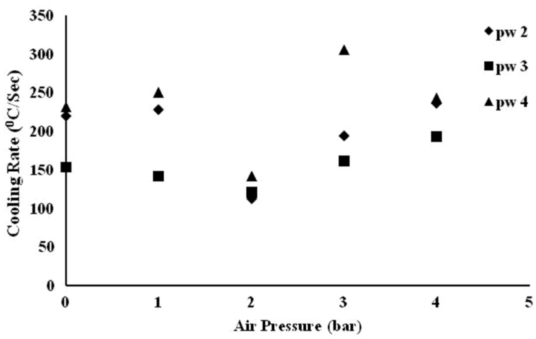

Fig. 10 Effect of air-water pressure on cooling rate at plate centre

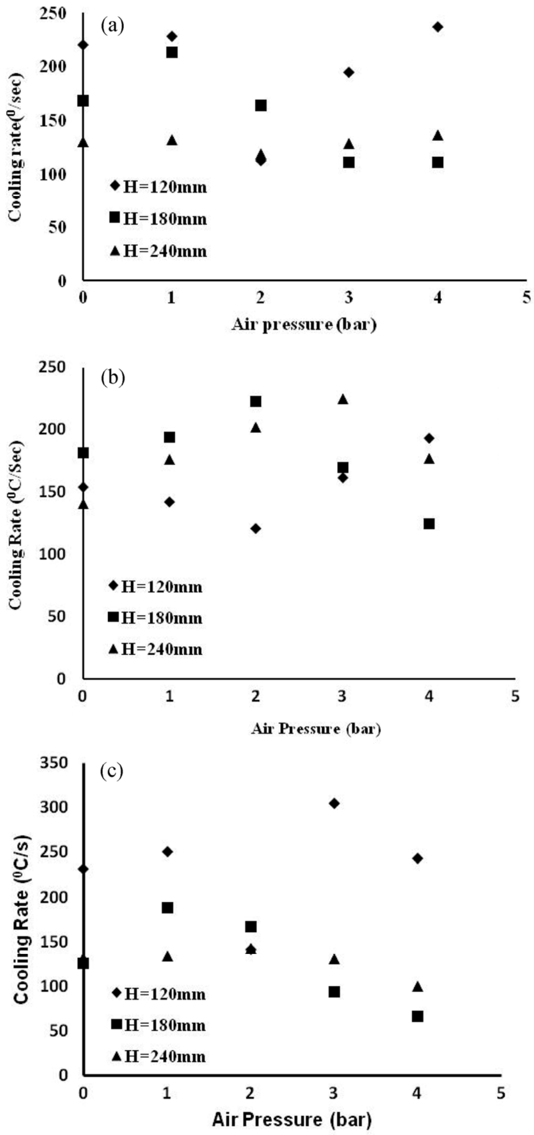

Fig. 11 Effect of nozzle exit to plate distance on cooling rate at plate centre for (a) Pw = 2 bar, (b) Pw = 3 bar and (c) 4 bar

Effect of flow rate

The heat transfer coefficients from the surface were plotted with respect to the air pressures to examine the effect of water pressure or flow rate on the heat transfer coefficients. As illustrations, Figure 12 depicts the plots between HTC and air pressures for three different nozzle heights and 4 mm thick plate considered in the work for the centrally located thermocouple (TC3) on the steel plate surface.

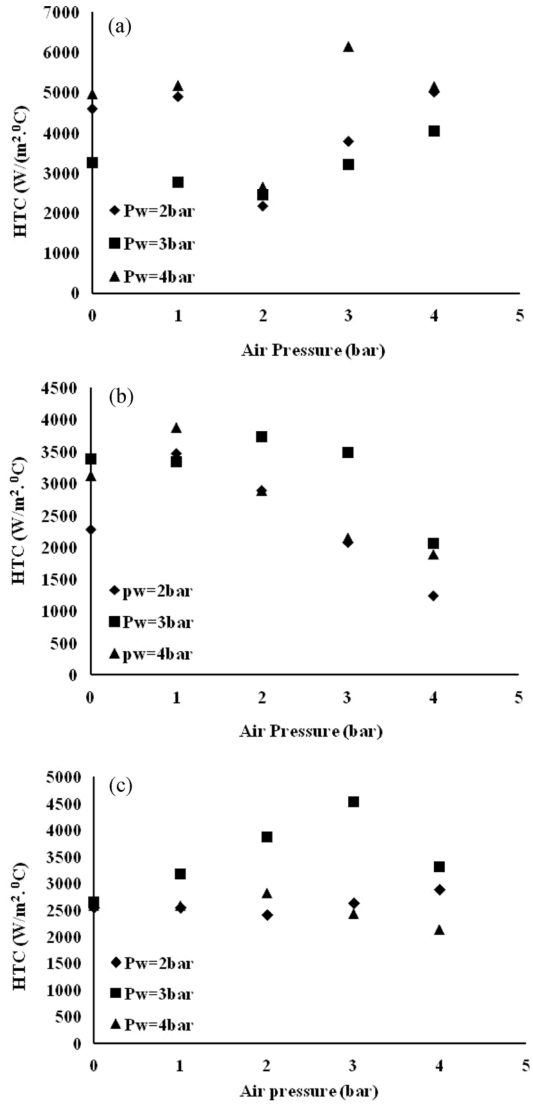

Fig. 12 Effect of flow rate on heat transfer coefficient at the centre of 4 mm thick plate for: (a) H = 120 mm (b) H = 180 mm and (c) H = 240 mm.

From Figure 12, it was observed that, there was no definite trend between HTC and flow rates. This was because of the fact that in this case cooling was caused by air-water spray at different nozzle height. The contributions of this parameter were significant and responsible for cooling effect. Hence water pressure alone cannot be used to improve the HTC. High flow rate in a spray quench accelerates cooling but there still exists the “limit” of the HTC in each specific operating condition. The nature of the distribution shows that an optimal value of the HTC exists. The optimal value of cooling rate can be obtained through optimisation of affected parameter, i.e., optimising the air-water pressure, nozzle height values.

The lesser was the air pressure, the higher water flow rate achieved and less atomization appeared. In one set of experiments, for a fixed water pressure of 4 bar and nozzle height of 120 mm, and variation of air pressure from 0 bar to 4 bar, the highest HTC achieved at the central place thermocouple, ranged from 1233.753 W/m^2 °C to 6134.738 W/m^2 °C.

Effect of plate thickness

The effect of variation of test plate thickness on the local heat transfer coefficient at water pressure of 4 bar and nozzle height of 240 mm was plotted and depicted in Figure 13.

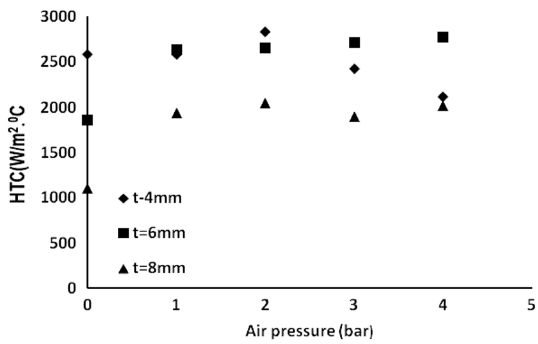

Fig. 13 Effect of plate thickness on heat transfer coefficient at the plate

Conclusions

The results of experimental investigation on thermal characteristics of spray cooling of hot steel plate under controlled parametric conditions have been reported. The cooling rates and heat transfer coefficients were determined for different water flow rates, nozzle heights, and plate thicknesses.

The surface-cooling rate decreased with an increased concentration of water quenchant. There was great fluctuation in the values of cooling rates with respect to water flow rate due to interruption of air in the spray. The contribution of both the quenchant was significant and responsible for cooling effect. Hence, water flow rate alone cannot be used to improve the cooling rate. The less was the thickness of the test plate, the more was the thermal performance of the spray cooling.

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