Applied Thermal Engineering 120 (2017) 537–548

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

High mass flux spray cooling with additives of low specific heat and surface tension: A novel process to enhance the heat removal rate

N.H. Bhatt [a], A.R. Pati [a], A. Kumar [a], A. Behera [b], B. Munshi [a], S.S. Mohapatra [a,*]

[a] Department of Chemical Engineering, National Institute of Technology Rourkela, Rourkela 769008, India
[b] Department of Metallurgical and Materials Engineering, National Institute of Technology Rourkela, Rourkela 769008, India

HIGHLIGHTS

- High mass flux spray minimizes the film boiling affect.
- Increment of contact area and latent heating period of coolant augments cooling rate.
- High mass flux spray with acetone eliminates Leidenfrost effect.
- Acetone added coolant significantly enhances the heat removal rate.

ARTICLE INFO

Article history:
Received 7 October 2016
Revised 29 March 2017
Accepted 31 March 2017
Available online 5 April 2017

Keywords:
Spray cooling
High mass-flux
Transition boiling
Heat transfer rate
Critical heat flux

ABSTRACT

High mass flux spray cooling is a good replacement of conventional cooling methods such as jet cooling and laminar cooling in metallurgical industries. However, the cooling rates obtained in spray cooling are still not sufficient for the production of high tensile strength and moderate hardenability steel. The challenging task in the conventional spray cooling is the elimination of film boiling phenomenon. The solution to such difficulties is the use of high mass flux spray which generates high momentum droplets that penetrates the vapour film and almost excludes the film boiling affect. Along with the aforesaid advantage, the high mass flux spray also creates low residence time that leads to incomplete evaporation and as a consequence, the obtained heat transfer rate is not significant. Hence, the heat removal rate needs to be further enhanced. This can be achieved by increasing the heat transfer area and lowering the sensible heating time. So, in the current work, coolants of low specific heat and surface tension are prepared by separately mixing water with benzene, acetone and *n*-hexane in different combinations to see the effects of specific heat and surface tension on heat transfer rate. The substrate used was a square AISI 304 steel plate (100 × 100 × 6 mm). The surface temperatures and heat fluxes were calculated by using INTEMP software. Before experimentation, the mass flux and nozzle to plate distance were optimised. The result shows significant augmentation of heat removal rate with an increment in critical heat flux of 40, 30 and 20% with acetone, *n*-hexane and benzene, respectively. Moreover, mathematical correlations are developed using Design Expert software to determine the heat transfer coefficient at different properties of coolants.

1. Introduction

The fabrication of light weight aircraft, nuclear reactor and manufacturing of high pressure gas pipelines need metal with high tensile strength and moderate hardenability [1–4]. These properties can be achieved by conducting fast cooling from its austenitization temperature (>900 °C) [5,6]. The achievement of high cooling rates (>300 °C/s) is a very difficult task to accomplish in the said temperature range because of the early occurrence of Leidenfrost effect [7,8]. In Leidenfrost effect, a vapour layer covers the hot surface and heat transfer rate drastically reduces. The elimination or the minimization of Leidenfrost effect has been the main challenging task in the development of appropriate heat treatment process for the achievement of above mentioned mechanical properties in steel.

The conventional cooling methodologies applied in metallurgical industries comprise of laminar syphon, different types of water jets and low mass flux spray. As these processes deliver very slow

---

* Corresponding author at: Room No-16, Department of Chemical Engineering, National Institute of Technology Rourkela, Rourkela 769008, India.
E-mail address: mohapatras@nitrkl.ac.in (S.S. Mohapatra).

http://dx.doi.org/10.1016/j.applthermaleng.2017.03.137
1359-4311/

Abbreviations

PID	proportional integral derivative
DAQ	data acquisition system
T_1, T_2, T_3	thermocouple locations in plate
T	temperature, °C
k	thermal conductivity, W/m °C
C_p	specific heat, J/kg °C
F_w	volumetric flow rate of water, m^3/s
$m_{f_{local}}$, m_{f_i}	local mass flux at i^{th} location, kg/m^2 s
$m_{f_{avg}}$, I_d	average mass flux, kg/m^2 s
M_w	mass of water collected, kg
μ	viscosity of coolant, Pa s
ΔT	temperature difference, °C
OES	optical emission spectrophotometer
AISI	American iron and steel institute
n	number of locations at which local impingement densities were measured
E	cooling effectiveness
q	surface heat flux, W/m^2
h_v	latent heat of vaporization, J/kg
C_{pl}, C_{pv}	specific heats of coolant in liquid and vapour phases, J/kg °C
T_s, T_l, T_w	temperatures of saturation, coolant and surface of hot plate, °C
ρ	density of coolant, kg/m^3
v_d	mean velocity of droplet, m/s
D	diameter of droplet, μm
σ	surface tension of coolant, N/m
t	time, s
d_t	diameter of the water collecting tube, m
Δt	time interval of water collection, s
CHF	critical heat flux, MW/m^2
SHF	surface heat flux, MW/m^2
HTC	heat transfer coefficient, kW/m^2 °C

cooling rates (<100 °C/s), hence it is difficult to produce steel with above mentioned properties. Among all the above stated cooling methodologies, spray cooling is found to be a promising cooling technology. However, in case of low mass flux spray cooling, complete elimination of vapour and liquid film affects are not possible [9–11].

The possible way to minimize the Leidenfrost effect is by using high momentum coolant droplets that penetrates the liquid and vapour films. Moreover, it also swaps away the partially evaporated droplets and prevents the merging of droplets into liquid or vapour film. Generation of high momentum droplets need high mass flux as reported by previous researchers [12–14]. They observed that with rising mass flux, the heat removal rate increases; however, the maximum considered mass fluxes were 20 and 30 kg/m^2 s, respectively. From the above discussed literature, it can be concluded that further rise in mass flux may enhance the cooling rate. Hence, further research on high mass flux spray (>30 kg/m^2 s) is required.

The heat transfer rate is a function of heat transfer area, latent heat extraction rate and droplet residence time. The heat transfer area or the contact area between the coolant droplet and the solid surface depends on the contact angle. By decreasing the contact angle of coolant droplet with the solid surface, high heat transfer area can be generated for droplet evaporation [15–17]. This can be achieved by adding some additives that can reduce the surface tension of the coolant. Chandra et al. [18] studied the effect of varying solid-liquid contact angle on the evaporation of coolant droplets impinging on stainless steel plate. They showed that by adding surfactants, not only the contact area was increased but also the thickness of the impinged coolant droplet was reduced significantly, further enhancing the heat transfer rate. Qiao and Chandra [19,20] investigated the surfactant added spray cooling. They found that the addition of surfactant enhanced the nucleate boiling heat flux by up to 300%. Furthermore, the information reported by Cheng et al. [21] disclosed the spray cooling enhancement by ethanol-water mixture. The cooling enhancement achieved due to the decrement of contact angle is not still significant. In addition to the above, the literature also reveals that the dissolved salt in the surfactant enhances the heat transfer rate by changing the heat transfer mode from convective to conductive [14,22]. The dissolved surfactant and salt deposit on the surface of the plate and as a consequence, the surface morphology changes [22–24]. Hence, these processes need to be further enhanced for the attainment of higher cooling rates and better morphology.

Along with the contact angle, the heat transfer is also influenced by latent heat extraction period and residence time. So far, no attempt has been made to augment the heat transfer rate by increasing the latent heat extraction period at very high initial surface temperature. For a fixed droplet residence time, the latent heat extraction period can be increased by decreasing the sensible heat extraction period. This can be attained by lowering the specific heat of the resultant coolant and this process in turn reduces the time required to reach the saturation temperature. The presence of benzene, acetone or *n*-hexane in coolant droplet reduces the specific heat and decreases the contact angle. Furthermore, the use of high mass flux spray generates high momentum droplets and lowers the residence time. In the current work, by the combined effects of reduction of specific heat, contact angle and residence time of the coolant and increment of droplet momentum, the heat transfer rate is expected to enhance significantly and the desired heat treatment methodology for the production of high tensile strength and moderate hardenability steel can be explored. Furthermore, in the current case, different additives are selected to enhance the spray cooling with two considerations: (1) the required amount of the additive to be added in the coolant; and (2) to see the effects of specific heat and surface tension on heat transfer rate at different combinations.

In the current study, experiments were conducted with different coolants containing various additives in water such as benzene, acetone and *n*-hexane. The concentration of these additives were also varied in different ranges depending on their solubility in water. Initially, the nozzle to plate distance (height) and flow rate (mass flux) were optimised experimentally. At optimum height and flow rate, further experiments with various coolants were conducted. After experimentation, the surface heat flux and temperature were calculated by using an inverse heat conduction software (INTEMP). The result reveals that all the additives were able to enhance the heat transfer rate at different magnitudes.

2. Experimentation

2.1. Experimental set-up

As shown in Fig. 1, an experimental set-up was fabricated to conduct the experiments. The whole set-up is divided into mainly three sections namely the heating, spraying and a data recording system.