International Journal of Heat and Mass Transfer 110 (2017) 330–347

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Enhancement of heat transfer rate of high mass flux spray cooling by ethanol-water and ethanol-tween20-water solution at very high initial surface temperature

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ARTICLE INFO

Article history:
Received 6 June 2016
Received in revised form 7 February 2017
Accepted 24 February 2017

Keywords:
Quenching
Droplet
Contact angle
Film boiling
Transition boiling
Foaming
Impingement density

ABSTRACT

Spray cooling is an efficient cooling technology over conventional cooling methods such as jet cooling on run-out table. However, the achieved cooling rates are still not enough for some specific applications. The main obligation in achieving high cooling rates is the occurrence of film boiling phenomenon. In the absence of any information on the heat transfer augmentation techniques of spray cooling at very high initial surface temperatures (~900 °C), the present work deals with enhancement of spray cooling at the aforesaid initial temperature by using different coolants which enhance the heat removal rate by creating high heat transfer area and decreasing the stability of the vapour and liquid film on the hot plate. For the experimental investigation, spray cooling experiments were conducted at 900 °C initial surface temperature on a 6 mm thick AISI 304 steel plate (100 × 100 mm) by using different coolants. The surface temperature and heat flux have been calculated using INTEMP software. For the understanding of heat transfer mechanism, the coolants properties at different concentrations and spray behavior at different flow rates were measured. The ethanol-water spray cooling demonstrates that the heat removal rate increases with increasing ethanol concentration by decreasing contact angle. The reduction in the contact angle results in increasing heat transfer area and decreasing the vapour-bubble coalescence rate. However, beyond ethanol concentration of 500 ppm, the excessive occurrence of the foaming decreases the heat removal rate. Further, the heat transfer rate is tried to enhance by adding tween-20 surfactant which lowers the contact angle significantly with the controlled characteristics of foaming. In the case of ethanol-water-tween 20 mixture spray, the achieved critical heat flux (2.1 MW/m^2) is 1.6 times that of pure water (1.3 MW/m^2). Due to the above mentioned favorable conditions for fast cooling, a maximum cooling rate of 141 °C/s is achieved.

1. Introduction

The high quenching rate of metals at the high initial surface temperature (>900 °C) is the main requirement of metallurgical industries for the production of some specific materials [1,2]. However, the achievement of high cooling rate is a difficult task in the said temperature range. It is because the heat transfer lies in the film boiling or transition boiling regime. In these regimes, a vapour layer forms over the surface of the metal that obliges the direct contact of the incoming coolant with the hot metal which in turn reduces the heat transfer rate drastically. Hence, the achievement for the high quenching rate is the main thrust for the further development of cooling enhancement techniques of the existing cooling processes used in the metallurgical industries [3–7].

Currently, in metallurgical industries, jet cooling or laminar cooling is used [8]. The main disadvantage of the present cooling methods is the slow quenching rate at high initial surface temperatures [9]. Spray cooling is highly advantageous over the laminar and jet cooling techniques in terms of heat transfer rates, heat transfer area and uniformity. It produces water droplets and these droplets contain high specific area for heat transfer which is several times higher than the pool boiling, laminar cooling or jet cooling heat transfer area. Hence, the heat flux and heat transfer rate increase [10]. This proves that spray cooling is an exceptionally productive means for achieving high heat fluxes with low coolant mass flux at lower wall superheats. However, at very high surface temperatures, the achievement of high heat flux by spray cooling has been a challenging task for the current researchers.

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.02.094
0017-9310/

Nomenclature

T	surface temperature, °C
$T1$	thermocouple 1 (20 mm from edge)
$T2$	thermocouple 2 (50 mm from edge, i.e., centre)
$T3$	thermocouple 3 (70 mm from edge)
F_w	volumetric flow rate of water, m^3/s
$\mathrm{I_d}$	impingement density, kg/m^2 s
F_a	volumetric flow rate of air, m^3/s
E_c	concentration of ethanol, ppm
S_c	concentration of surfactant (Tween 20), ppm
M_w	mass flow rate of water, kg/s
Δt	time interval, s
d_t	diameter of tube, m
ΔT	temperature difference, °C
OES	optical emission spectrophotometer
AISI	american institute of standards
CMC	critical micelle concentration (PPM)
PDA	Phase Doppler Anemometer
$I_{d_{avg}}$	average impingement density, kg/m^2 s
I_{d_i}	local impingement density at *i*th location, kg/m^2 s
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
We	Weber number
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
H	distance of nozzle from plate, mm
$\mathrm{q_{avg}}$	average surface heat flux, MW/m^2
C	concentration of ethanol in ethanol-water mixture, ppm
c	concentration of ethanol in ethanol-tween 20-water mixture, ppm
h_{avg}	average heat transfer coefficient, W/m^2 K

The trouble in accomplishing a higher heat exchange rate at high surface temperatures in water spray cooling is clarified by the Leidenfrost phenomena [11,12]. In case of high mass flux spray cooling, due to the low evaporation rate and high falling rate of water droplets a thin layer of water forms on the hot plate and in between, the water layer and the hot plate, a vapour layer forms because of evaporation. This phenomenon is analogous with the film boiling or transition boiling phenomenon of pool boiling process [12]. However, the main difference between the high mass flux spray boiling and pool boiling is that the thin liquid layer is continuously replaced in case of spray boiling due to the attainment of horizontal motion of coolant mass after impingement on the plate. The momentum of thin water film increases with the increasing mass flux. The said phenomena are shown Fig. 1 (a) and (c), respectively. Due to the aforesaid reason, the film boiling effect decreases; however, still the achieved cooling rate is not sufficient for the production of the above mentioned materials. Hence, for the enhancement of spray cooling in transition/film boiling regime more investigation is required.

The heat transfer rate in case of spray boiling depends on the intensity of the film boiling the droplet momentum and the contact area of the coolant droplet with the hot surface. The stability of the liquid and vapour film on the hot plate decides the strength of the vapour film which forms during the transition and film boiling. To overcome the film boiling effect, the droplet has to penetrate the vapour film as well as the liquid film and this is possible if the droplets have high momentum which is directly related to the mass flux of the spray. The information reported by Al-Ahmadi et al. [13] and Wendelstorf et al. [9], corroborate the aforesaid argument. According to them, the heat removal rate increase with the

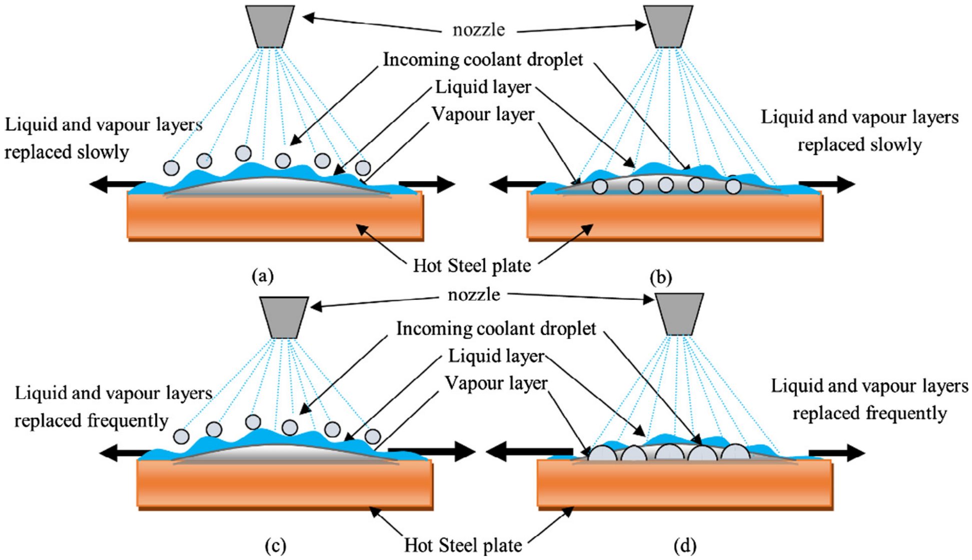

Fig. 1. Schematic view of spray cooling phenomenon with (a) low droplet momentum and slow liquid/vapour layer renewal; (b) high droplet momentum with high contact angle and slow liquid/vapour layer renewal; (c) low droplet momentum with low contact angle and slow liquid/vapour renewal; (d) high droplet momentum with low contact angle and high liquid/vapour layer renewal.