



Enhancement of heat removal rate of high mass flux spray cooling by sea water



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ABSTRACT

The main obligation in achieving high cooling rates in case of spray cooling at high surface temperature is the occurrence of film boiling phenomenon. Although the high mass flux spray reduces the film boiling affect, still, the heat transfer rate is not significant and hence, this process needs to be enhanced. In the absence of any information on the heat transfer augmentation technique, the present work deals with the enhancement of high mass flux spray cooling at very high initial plate temperature by using sea water. The sea water spray cooling process increases the heat removal rate by creating high heat transfer area for the droplet evaporation and by reducing the vapour pressure of vapour film on the hot plate. The cooling ability of the sea water spray is compared with the coolants (salt added water, surfactant added water and salt added water) which partially depict the properties of sea water. For the experimental investigation, spray cooling was conducted at 900 °C initial surface temperature on a 6 mm thick AISI 304 steel plate (100 × 100 mm) by using sea water and also aforesaid coolants at different concentrations. The surface heat flux and surface temperature have been predicted using the solution of the Inverse Heat Conduction Problem (IHCP). For the understanding of heat transfer mechanism, the properties of coolants (contact angle, thermal conductivity, density, specific heat and mass diffusivity) at different concentrations and spray behaviour (droplet diameter, spray pressure, droplet velocity and spray impingement density) at different flow rates were measured. The physical properties of the coolant reveal that the contact angle decreases with the increasing salt concentration up to 0.1 M and further increment in salt concentration enhances the contact angle. From the thermal properties of the coolant, it is observed that thermal diffusivity in sea water is higher than salt added water. The sea water spray cooling asserts that the heat removal rate increases with the increasing percentage of sea water in the mixture of seawater and pure water due to the salt deposition on the hot surface. However, the achieved heat removal rate is lower than that of salt added water due to the comparatively less amount of salt deposition in case of sea water spray. Furthermore, the combined effect of the salt deposition and lowering of vapour pressure in vapour film phenomena produce better heat removal rate than the pure water and surfactant and salt added water. In comparison between sea water and surfactant added water spray cooling, the former produces higher heat removal rate because of the dominance of salt deposition phenomenon over the lowering of contact angle property. In case of sea water spray, the achieved critical heat flux (1.55 MW/m²) is 1.3 times that of pure water (1.2 MW/m²); moreover, the enhanced critical heat flux is obtained at 170 °C higher surface temperatures. In addition to the above, the enhancement by NaCl added water spray is almost 1.6 times that of pure water. Due to the above mentioned favourable conditions for the fast cooling, the maximum cooling rates of 115 °C/s and 135 °C/s are achieved with sea water and NaCl added water sprays, respectively.

1. Introduction

The development of high temperature quenching technologies for cooling electronic components, enhanced heat removal rate in nuclear power plant. The heat treatment of some specific products in the different metallurgical processes have been a challenging task for the present researchers [1–3]. In such cooling operations, the occurrence of

early film-boiling or Leidenfrost phenomenon massively reduces the heat transfer rate. This phenomenon occurs when the temperature of the plate is higher enough than the liquid/coolant's boiling point. Due to this a vapour layer appears in between the hot plate and the water droplet and as a consequence the incoming droplet levitates over the hot surface instead of making contact with it [4].

The conventional cooling methodologies such as water jet and water

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Nomenclature

CHF	critical heat flux
DAQ	data acquisition system
OES	optical emission spectrophotometer
q	heat flux, MW/m ²
T ₁ , T ₂ , T ₃	locations of three sub-surface thermocouples
I _d	impingement density, kg/m ² s
M _w	mass of water collected, kg
d _t	diameter of the tube, m
Δt	time interval, s
F _w	water volumetric flow rate, m ³ /s
NaCl	sodium chloride
θ	Contact angle, degree
Tween 20	polyoxy ethylene (20) sorbiton monolaurate
T _s	surface temperature, °C
k _{salt} , k _{plate}	thermal conductivities of salt (NaCl) and AISI 304 steel plate
We	Weber number
T1, T2	temperatures of different sides of the droplet, °C
R _d	residence time of each droplet, s
A _d	droplet area, m ²
m _d	mass of each droplet, kg
CHF _{Temp.}	surface temperature corresponding CHF, °C
I _{d avg}	average impingement density, kg/m ² s

S _c	concentration of salt, M
C _c	surfactant concentration, ppm
SW _c	sea water concentration, %
F _a	air flow rate, N m ³ /h
T _{1(measured)} , T _{2(measured)} , T _{3(measured)}	measured temperatures at locations T ₁ , T ₂ , T ₃
T _{1(predicted)} , T _{2(predicted)} , T _{3(predicted)}	predicted temperatures at locations T ₁ , T ₂ , T ₃
Ra	arithmetic mean of roughness value, μm
v _{dp}	velocity of the droplet or liquid film on the hot plate, m/s
r	distance travelled by the droplet or liquid film on the hot plate, m
X _t	6 mm
f	droplet detachment frequency, 1/s
H	nozzle height, m
q _{CHF}	critical heat flux, kW/m ²
β	spray cone angle, degree
h _{fg}	latent heat of vaporization, J/kg
d ₃₂	sauter mean diameter, m
ρ _v	vapour density, kg/m ³
ρ _l	liquid density, kg/m ³
σ	liquid surface tension, N/m
C _p	liquid specific heat, J/kg/K
ΔT _{sub}	the sub cooling temperature, °C

spray used in the metallurgical industries are not appropriate for the production of some specific materials because of the requirement of high cooling rate at high initial surface temperatures [5]. The inadequate cooling rates produced by the above mentioned processes describe the limitations of the present heat treatment technologies. Hence, for the fast cooling technologies, the conventional cooling processes used in the metallurgical industries need to be further enhanced [6].

Spray cooling produces better heat transfer rate compared to the conventional jet cooling. The spray cooling has two major advantages: high heat removal rate and uniform cooling on the hot surface. Furthermore, it is observed that the spray cooling is a cost effective process than air atomized spray [7]. However, the produced quenching rates by the spray cooling is not yet sufficient for fast cooling at very high initial surface temperatures [8].

In spray cooling, fine droplets of the coolant impinge individually on the hot surface to achieve uniform heat removal [9,10]. In high mass flux spray cooling (20 kg/m² s), with low evaporation rate, a thin layer of the vapour forms in between the hot plate and liquid droplet which is the Leidenfrost effect [11]. As a consequence, the heat transfer occurs from the hot plate to the droplet by convection and radiation which are responsible for decrement of heat transfer rate.

The film boiling effect becomes stronger with the increasing residence time of the vapour and liquid film on the hot plate. The higher momentum coolant droplets at high mass flux spray enable the droplets to partially penetrate and impinge on the hot plate. Then, after partial evaporation, the droplet becomes part of the liquid and vapour films. Although with the increasing mass flux, the developed vapour layer and the liquid layer are replaced very quickly; however, still the heat transfer mechanism does not change [12,13]. As a result, high mass flux spray also can not eliminate the film boiling effect completely [14]. It is known that changing the heat transfer mechanism between hot surface and droplet or liquid layer from the convective to conductive mode, a significant improvement in heat transfer rate is achieved [15].

During the evaporation of salt added water droplet, the deposition of salt occurs on the hot plate and the deposited salt penetrates the vapour film and comes in contact with the incoming coolant droplets or the liquid film. The heat transfer takes place from the hot plate to the

coolant through the deposited salt by conduction and as a consequence the heat transfer rate increases [14]. The reported enhancement is found to be 42%. Cui et al. [16] studied the effect of salt in water spray cooling performance at low initial plate temperature (< 300 °C) and mass flux (< 30 kg/m² s) of the coolant. Both the conditions are not suitable for the high temperature applications. The presence of surfactant increases the heat removal rate of spray cooling due to increment of heat transfer area [17–21]. Furthermore, the reported information [22] reveals that enhancement by sub cooling of the coolant delays the onset of boiling but declines the slope of the nucleate boiling regime of the spray boiling curve. Refiners et al. [23] studied heat transfer during cooling in continue casting by water spray with various initial water temperatures. They noticed that heat transfer coefficient enhances with increasing the degree of sub cooling and spray mass flux. But, the said works have been reported at very low initial substrate temperatures (Table 1) and mass fluxes of the coolants. The enhancement of air atomized spray cooling due to surfactant and salt were reported at high initial surface temperatures [24,25]; however, for very high initial surface temperature (~ 900 °C), the effects of surfactant and salt in spray cooling have not been disclosed so far.

The reported result clearly demonstrates the enhancement of heat removal rate in the transition and nucleate boiling regimes. The aforesaid regimes start at very low surface temperatures in case of low mass flux spray cooling; however, in case of high mass flux spray cooling both the boiling regimes appear at very high initial surface temperature. The mechanism of the heat transfer is expected to be same for both low and high mass flux cases. The above literature survey depicts that the addition of salt and surfactant increases the heat

Table 1

The maximum considered substrate temperature by the different researchers.

Researchers	Maximum substrate temperature (°C)
Cui et al.	240
Chandra et al.	220
Reiners et al.	250

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