Applied Thermal Engineering 138 (2018) 603–617

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

The heat transfer characteristics and rewetting behavior of hot horizontal downward facing surface by round water jet impingement

Avadhesh Kumar Sharma, Mayank Modak, Santosh Kumar Sahu*

Discipline of Mechanical Engineering, School of Engineering, Indian Institute of Technology Indore, Madhya Pradesh 453552, India

HIGHLIGHTS

- Tests are conducted on downward facing surface with water jet impingement.
- Infra red thermal imaging technique is used to measure temperature data.
- Surface heat flux distribution and location of maximum surface heat flux are studied.
- Rewetting time, rewetting temperature and rewetting velocity are estimated.
- Correlations are proposed for various heat transfer and rewetting parameters.

ARTICLE INFO

Keywords:
Liquid jet impingement
Surface heat flux
Infrared thermal imaging
Rewetting
Peclet number

ABSTRACT

Present paper reports the heat transfer characteristics and rewetting behavior of 0.15 mm thick hot horizontal stainless steel foil (SS-304) by circular impinging jet from bottom side through experimental investigation. The transient temperature of the hot foil is recorded by using thermal imaging camera (A655sc, FLIR system). Tests are performed for a varied range of Reynolds number (Re = 2500–10,000), nozzle to plate distance (z/d = 4–10) and initial surface temperature 500 ± 10 °C. Transient temperature obtained from thermal imaging camera is used to evaluate various parameters such as surface heat flux distribution, rewetting time, rewetting temperature and rewetting velocity. Surface heat flux is found to attain maximum value at the stagnation point and gradually decreases in the radial direction away from the stagnation point. Based on the experimental investigation correlations have been proposed to predict various parameters such as surface heat flux, rewetting temperature and non-dimensional rewetting velocity as a function of various parameters, namely, Reynolds number, non-dimensional radial distance and non-dimensional nozzle to plate distance.

1. Introduction

Impinging jet cooling is receiving significant attention due to its ability to attain high heat transfer rate. Impinging jets with liquid as working fluid are extensively used in various industrial processes, namely, metals and glasses process industries, most recently in cooling of various electronic components and cooling of fuel pins during the loss of coolant accidents [1]. During the loss of coolant accident (LOCA), the clad tubes involving fuel pins becomes overheated due to non-function of the primary cooling system. In such a case, an emergency core cooling system is operative to remove the excessive heat from fuel pins.

As the water jet comes in contact with the hot surface, a vapor film is formed on the hot surface. This vapor film restricts the direct interaction between water and hot surface. Subsequently, due to the poor conduction through the vapor film, the heat transfer reduces. As the process continues the vapor film collapses and the liquid wet the hot surface. This phenomenon of liquid-surface contact re-establishment is termed as a rewetting phenomenon. The temperature corresponds to this is termed as rewetting temperature. The time taken to rewet the surface after the liquid jet impingement onto the hot surface is termed as wetting delay or rewetting time [2]. Rewetting is considered as a highly transient heat transfer process. The rewetting process is mainly responsible for the rapid cooling of the hot surface.

In addition to this, the mode of interaction of coolant jet with hot surface plays an important role in the performance. Earlier, Groenerveld and Snoek [3] reported six different types of fluid wall configurations to describe the occurrence of the rewetting phenomenon. The rewetting behavior of 54-rod bundle by in-bundle coolant injection through experimental investigation has been reported by Patil

* Corresponding author.
E-mail address: sksahu@iiti.ac.in (S.K. Sahu).

https://doi.org/10.1016/j.applthermaleng.2018.04.050
Received 26 July 2017; Received in revised form 6 April 2018; Accepted 8 April 2018
Available online 18 April 2018
1359-4311/

Nomenclature

A	surface area of test specimen (mm^2)
Bi	Biot number, ($h\delta/K$)
c_p	specific heat capacity of the material (kJ/kg K)
d	diameter of nozzle (mm)
k	thermal conductivity (W/m °C)
Pe	Peclet number
Q	coolant flow rate (g/s)
q	surface heat flux (MW/m^2)
q_{max}	maximum surface heat flux (MW/m^2)
r	radial location in downstream direction away from the stagnation point (mm)
R_a	average roughness value of surface (μm)
Re	Reynolds number, ($\rho vd/\mu$)
Δr	distance between two pixel positions (mm)
T	surface temperature of the test specimen (°C)
t	time (s)
T_r	rewetting temperature (°C)
t_r	rewetting time or wetting delay (s)
T_s	saturation temperature (°C)
Δt	time taken by the wet front between two pixel points on the target surface (s)
u	rewetting velocity (mm/s)
V	volume of the material (mm^3)
v_j	jet velocity (m/s)
z	nozzle to plate distance (mm)

Greek symbols

ε	emissivity of the test specimen
δ	thickness of the test foil (mm)
ρ	density of test material kg/m^3

et al. [4]. In their study, the central coolant tube is used to supply coolant at different axial levels in the form of the jet through various circumferential holes of each level. The rewetting behavior of vertical hot rod by various coolant distributions such as uniform film flow or impingement from discrete jets have been studied by Sahu et al. [5]. Agrawal and Sahu [6] reported the surface heat flux distribution and rewetting behavior of hot vertical foil by round water jet impingement. The authors used thermal imaging technique to measure the surface temperature variation during transient cooling. In addition to this, it is necessary to assess this heat removal process during rewetting phenomenon. The location and propagation of maximum heat flux during impingement cooling was reported by various researchers through experimental investigations [7,8]. The heat transfer behavior of hot surface primarily depends on the mode of interaction of coolant and the test surface. Based on the industrial applications, and design of the reactor core, various modes of coolant injection can be adapted to cool the hot surface. The inclination of coolant jet with hot surface plays an important role in the heat transfer. It may be noted that the orientations of the hot surface are either vertical or horizontal. Attalla and Salem [9] carried out tests to understand the effects of Reynolds number, nozzle to plate distance and inclination of the jet on heat transfer from a horizontal flat plate during jet impingement. Modak et al. [10] carried out an experimental investigation to analyze the heat transfer characteristics of a hot vertical stainless steel foil by circular impinging jets of pure water and Al_2O_3–water nanofluids. In addition to this, the authors carried out experiments to analyze the rewetting behavior of hot vertical surfaces by using Al_2O_3–water nanofluids [11] and aqueous surfactant solution [12]. The authors [10–12] employed infrared thermal imaging technique to record the transient temperature during cooling.

In case of a hot horizontal surface, the cooling is achieved by employing the bottom jet, top jet and both top and bottom jet impingement [13]. The heat transfer and hydrodynamics in case of bottom jet cooling and top jet cooling are different. In case of top jet impingement, five different heat transfer regimes are observed as reported by Zumbrunnen et al. [14]. In such a case, the maximum heat flux is observed in the vicinity of the wetting front on the transition boiling regime of the boiling curve [15]. During top jet impingement, various boiling regimes include single-phase forced convection, nucleate/transition boiling, forced convection film boiling, the agglomerated pools, and radiation and convection to surroundings. On the contrary, in the case of bottom jet impingement, four boiling regimes are observed including the above-mentioned regimes except the agglomerated pools [16]. This essentially differentiates the heat transfer mechanism, especially the propagation of wet front on the hot surface. The propagation of wet front is higher in case of bottom jet impingement compared to the top jet impingement. Also, for the same coolant flow rate, the jet velocity at the vicinity of the hot surface is higher in case of top impingement due to the effect of gravity [13]. In bottom jet impingement, due to gravitational force, water removes from the impinged surface and heat extracted is restrained to a smaller effective area as compared to top impingement. Wang et al. [13] investigated the heat transfer characteristics of a circular nozzle jet impinging on the top and bottom side of the plate. The authors [13] reported that for the given operating conditions, the heat flux from the top surface is higher as compared to the bottom one. This difference is due to the effect of gravitational force on the jet velocity (v_j). Jet velocity plays a crucial role to generate higher cooling performances during jet impingement on top and bottom sides of the plate.

The effect of nozzle to plate distance on heat transfer for downward jet has been reported by various researchers. During downward jet impingement, with water as fluid, Stevens and Webb [1] reported for single phase free liquid jets that increasing nozzle to plate spacing generally decreased the heat transfer slightly. Abdelsalam et al. [17] carried out experimental analysis by impinging free water jet onto a heated flat plate and reported that decreasing the nozzle to plate spacing slightly increased the cooling rate by counter acting effects of gravity acceleration and jet momentum dispersion. Issa [18] carried out an experimental study for the quenching of a stainless steel plate using oil jet impinging on the bottom surface of the plate and reported that nozzle to plate distance has an effect on heat transfer. However, the effect of oil pressure is much stronger than the effect of nozzle to plate distance. Attalla and Saleem [9] concluded for the stagnation region that the maximum heat transfer happens at a jet to plate distance about six times the jet diameter for vertical circular jet impinging on a flat surface.

The rewetting behavior of hot horizontal surface with impingement by round water jet from the top side was experimentally studied by Agrawal et al. [19]. The authors reported a correlation for the rewetting velocity and maximum surface heat flux from the test data. Tests have been performed to study the heat transfer characteristics of a hot horizontal surface with vertical water jet impingement [17,20].

A host of experimental studies have been made to analyze the heat transfer characteristics of the hot surface by bottom jet impingement [16,21–25]. Woodfield et al. [21,23] carried out the experiments to study the cooling of the heated cylindrical blocks by bottom impinging jet. The surface temperature is varied within 250–600 °C. The authors identified two regions in the wet patch, such as the central region with no apparent boiling and an outer annular region with violent liquid boiling. The authors [21] mounted various thermocouples at a certain depth from the impingement surface and surface temperature has been estimated by employing inverse heat conduction. Yadav et al. [25] carried out an experimental investigation to analyze the heat transfer