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Experimental study of the hydrodynamic and heat transfer of free liquid jet impinging a flat circular heated disk

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Abstract

This study concerns the hydrodynamic and the thermal characteristics of the free liquid jet impinged a heated disk. The thin liquid layer depth is measured along the axial and the radial directions using the laser induced fluorescence and image processing. The experimental results are compared to the laminar and turbulent theories of Watson [E.J. Watson, The radial spread of a liquid over horizontal plane, J. Fluid Mech. 20 (1964) 481–500]. The influence of the temperature and the liquid flow rate on the structure of the impingement jet is studied. The profiles of the axial and the radial velocities are measured along the flow. The hydraulic jump radius is measured for different Reynolds number and temperature of the flow. The heat transfer coefficient is measured in the stagnation zone and the experimental values are compared to the experimental data of Jiji and Dagan [L.M. Jiji, Z. Dagan, Experimental investigation of single-phase multijet impingement cooling of an array of microelectronic heat sources, in: Cooling Technology for Electronic Equipment, International Symposium Honolul U HA, 1988, pp. 333–350]. The distribution of the local heat transfer coefficient is determined by solving the inverse heat conduction problem.

Keywords: Free liquid jet; Layer depth; Local velocity; Local heat transfer; Hydraulic jump radius

1. Introduction

Jet impingement heat transfer has been employed in many practical applications for cooling and drying because it provided high heat transfer coefficient. In metal and plastic manufacturing industries, this cooling technique is applied to control the temperature histories during processing. The applications of liquid jet also included cooling laser, electronic equipments; cooling in internal combustion engines, and thermal control of high performance of computer components. Extensive numerical and experimental studies on heat transfer and hydrodynamics of liquid jet impingement have been reported in the literature [1–4]. When a circular liquid jet strikes a flat plate, it spreads radially in very thin film along the heated surface. Following many authors [5,6], the jet impingement flow is divided into five regions defined as: (i) the stagnation zone where the heat transfer is maximal, (ii) the viscous boundary layer zone where the dynamic boundary thickness is lower than the film thickness, (iii) the thermal boundary layer where the film thickness is higher than the thermal boundary layer, (iv) the fully thermal and viscous boundary layer region and (v) the hydraulic jump where the liquid sheet thickness is increased and the jump is associated with a Rayleigh–Taylor instability.

Jet impinging on a heated surface is depended on different parameters such as the temperature of the liquid, the orientation of the jet, the surface geometry, etc. Siba et al. [7] conducted an experimental study of the flow and heat transfer characteristics of a turbulent air jet impinging on a horizontal flat surface, and showed that

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Nomenclature

C_p	specific heat capacity (J/kg K)
D	heat exchange surface diameter (m)
d_i	nozzle diameter (m)
f	temperature function (K)
h	heat transfer coefficient (W/m^2 K)
J	residual functional (K^2)
$\dot{m}$	mass flow rate (kg/s)
N	angular nodes number
Nu_m	average nusselt number
Nu_0	Nusselt number in stagnation point
Nu_r	local nusselt number
Q	heat flux (W/m^2)
r	radius distance from stagnation point (m)
r_n	co-ordinate of measurement point (m)
R_2	radius of the heated surface (m)
R_{hyd}	hydraulic jump radius (m)
Re	Reynolds number based on nozzle diameter
S	nozzle to disk spacing (m)
T	calculated temperature (K)
T_j	jet temperature (K)
T_s	surface temperature (K)
T_{meas}	measured temperature (K)
U_j	radial velocity (m/s)
$V_{j,i}$	inlet jet velocity at $z = S$ (m/s)
z	axial coordinate (m)
z_n	coordinate of measured point (m)

Greek symbols

λ	thermal conductivity (W/m K)
θ	temperature variation (K)
Ψ	Lagrange multiplier
γ	descent parameter
δ	liquid layer depth (m)
μ	dynamic viscosity (kg/m^{2}s)
v	kinematic viscosity (m^2/s)
ρ	mass density (kg/m^3)
σ	surface tension (N/m^2)

Subscripts

m	mean value
n	measured points
w	wall
i	inlet
it	iteration number
j	jet
r	local value
s	surface

heat transfer is influenced by the turbulent fluctuations of the free stream velocity. Ma et al. [8] have analyzed the influence of Prandtl and Reynolds numbers, and nozzle to plate spacing for the vertical heaters impinged by submerged circular oil jets. An experimental study was conducted by Ma et al. [9] of local convective heat transfer for vertical heated surface cooled by an inclined impinging jet. The effect of jet inclination was examined in the range of the jet angle from 90° to 45°. The maximum heat transfer coefficient was found to decrease by increasing the jet inclination. Elison and Webb [10] studied the heat transfer from free-surface and submerged impinging liquid jets in the initially laminar, transitional and turbulent flow regimes. The heat transfer for the free surface jets is little dependant on the nozzle to plate spacing and the dependence on the Reynolds number is attributed to the surface tension effects. The heat transfer for single phase micro jets impingement was analyzed by Fabbri et al. [11]. They tested a number of jets varied from 61 to 397 and showed that the Nusselt number is more strongly dependent on the Reynolds number, Prandtl number and nozzle diameter.

Numerous studies are conducted in order to evaluate the heat transfer coefficient for the impingement jet on the horizontal or the vertical surface. The flow structure is analyzed by Stevens and Webb [12–14] for a water film formed by a circular jet impinging perpendicularly on a horizontal surface and the hydraulic jump location is correlated by the following equation:

$$\frac{R_{\mathrm{hyd}}}{d_i} = \alpha Re^{a} \tag{1}$$

where the parameters α and a are defined from the experimental results as 0.0061 and 0.82 respectively for the nozzle diameter (d_i) of injector in the range of 2.2–8.9 mm and for inlet Reynolds number in the range of 1000–52,000.

This brief bibliography shows that numerous studies on turbulent jet impinging over a heated surface are conducted in order to evaluate the average or the stagnation heat transfer coefficient in the steady state. Several authors have determined the heat transfer coefficient in the stagnation point from the total heat flux because measure the surface heat flux and temperature are difficult without perturbing the flow. Pan and Webb [15] measured the surface temperature using the infrared thermography. In this paper, the evolution of the local heat transfer coefficient is determined by solving the inverse heat conduction problem (IHCP). In the previous works, various numerical methods have been developed to solve IHCP for steady state and transient state [16–19]. In this study, the iterative regularization method is applied for solving the two-dimensional linear IHCP. The local and average thermal characterization