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Experimental and numerical study of the hydraulic jump of an impinging jet on a moving surface

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Abstract

The purpose of the present paper is to study experimentally a free impinging axisymmetric jet on a moving surface. Comparisons of the experimental data and the numerical simulations using Star CD software have been made in order to validate the numerical procedure. Since heat transfer efficiency of cooling process is controlled by hydrodynamic field, the first step is to check if numerical results are in agreement with experimental data. The final goal is to simulate the cooling of rolling process in steel making. Experiments have been carried out with tap water and with two nozzle diameters (17 and 20 mm).

Keywords: Impinging jet; Moving surface; Hydraulic jump

1. Introduction

Impinging jets are known to ensure high heat and mass transfer coefficients, so these are used in many industrial applications. In steel making, impinging water jets are widely used in rolling processes. In paper making, impinging air jets are also the best way to dry the paper. Experimental, analytical and numerical studies have provided numerous data on free impinging jets, submerged jets or confined jets; data are most often concerned with heat transfer capabilities of free or submerged impinging jets. The presence of a moving plate results in a much more complicated flow structure, but it is realistic in the potential industrial applications. As the heat and mass transfer beneath an impinging jet depend on the nature of the flow field, full understanding of the flow structure is necessary to understand the associated heat and mass transfer phenomena.

Valuable results on free surface impinging jets can be found in the literature. The theory of film flows is widely described in the precursor works of Watson [1]. Watson found analytically the expression of the velocity fields of the four flow regions [1] using boundary layer theory. He divided the flow radially into a stagnation region, a boundary layer region with surface velocity equal to the jet velocity, a region of decreasing free surface velocity, and lastly a hydraulic jump. So, he expressed the solution in a self-similar manner. Nakoryakov et al. [2] discussed Watson's analytical results with their experiments. Azuma and Hoshino [3] experimentally verified Watson's expression for laminar boundary layer, similarity region and film thickness using laser-Doppler measurements. Stevens and Webb [4] have compared measurements of the velocity profiles (LDV), layer depth and free surface velocity with analytical predictions. They have shown that the maximum velocity in the layer is not at the free surface for $r/d < 2.5$; thus, this

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Nomenclature

D	nozzle diameter (m)
D_{simu}	corrected nozzle diameter used for numerical simulation (m)
g	acceleration of gravity (m/s^2)
H	distance between nozzle and the plate (m)
h_{simu}	corrected distance between nozzle and the plate used for numerical simulation (m)
$\overline{H}$	dimensionless distance, $\left(\frac{H}{D}\right)$
Q	volumetric flow rate of the liquid jet (m^3/s)
R_{ju}	radius of the hydraulic jump (m)
$\overline{R_{ju}}$	dimensionless radius, $\left(\frac{R_{ju}}{D}\right)$
Re	Reynolds number of the jet, $\left(\frac{\rho \cdot V_j \cdot D}{\mu}\right)$
V_I	average impact jet velocity (m/s)
V_j	average jet exit velocity (m/s)
$V_{j_{simu}}$	corrected average jet exit velocity used for numerical simulation (m/s)
V_S	velocity of impingement surface (m/s)
$\overline{V}_S$	dimensionless surface velocity, $\left(\frac{V_S}{V_j}\right)$
We	Weber number, $\left(\frac{\sigma}{\rho \cdot V_j^2 \cdot D}\right)$
x, y, z	coordinates measured from the impingement point (m)
Y_{ju}	position of the first minimum (m)

Greek symbols

α_{water}	volume fraction of water
μ	dynamic viscosity (kg/m s)
ν	kinematic viscosity (m^2/s)
ρ_{water}	density of water (kg/m^3)
ρ_m	density of mixture (kg/m^3)
σ	surface tension (kg/s^2)

invalidated the assumptions of many analytical models for this region of the flow. So, for the last three or four decades, film flows have been widely studied; velocity fields of each region have been found and these can be used to study the convective heat transfer problems [4–6]. Bohr et al. [7] showed that the radius R_{ju} of the jump can be estimated through the scaling relation $R_{ju} \sim Q^{\frac{5}{8}} \cdot \nu^{-\frac{3}{8}} \cdot g^{-\frac{1}{8}}$ where Q is the volume flow rate, ν is the kinematic viscosity and g is the gravitational acceleration.

Despite the great practical importance in cooling of rolled metals, jet impinging on moving surface received much less attention. One can notice the studies of Zumbrunnen et al. [8,9]. In the case of plane jet, they have shown that the moving surface strongly influences the flow field and the heat transfer. The water from the nozzle is divided when it impinges the plate (moving or not); the flow can be opposed or in the direction same as that of plate motion. The transport of the fluid away from the stagnation line can be facilitated by the moving plate. However, on the other side, fluid is entrained and could penetrate again the impingement region (beneath the jet). For axisymmetric water jet impinging a moving plate, the flow structure is much more complicated because the jet divides in all directions, but one can observe the same phenomena of re-entrainment of the fluid. Zumbrunnen [8] solved the Navier–Stokes equations by similarity analysis; the heat and mass transfer distributions were determined by solving numerically the conservation equations for energy and species. He concluded that the influence of the surface motion on fluid flow is confined to a thin region which can be represented by the velocity boundary layer thickness for a plane jet impinging on a stationary surface. Convective heat transfer is unaffected by the surface motion when the surface temperature is constant along the impingement surface. But in the case of a spatially dependent temperature, convective heat transfer is dependent on the dimensionless surface velocity $\overline{V}_S$. In most applications using impinging jets, surface temperature decreases in the direction of surface motion. More recently, Chattopadhyay and Saha [10] numerically studied the flow field for the impinging of a rectangular submerged jet on a moving surface for moderately high Reynolds number ($Re = 5800$) using the large eddy simulation technique. They provided a large database of turbulent quantities for such a configuration.

2. Experimental set-up

The configuration considered is that of one axisymmetric impinging jet. The fluid used is water at 20 °C ($\rho = 1000$ kg/m^3 and $\mu = 10^{-3}$ Pa s). The jet impingement set-up used for the experiments is a transparent closed loop but which is opened to the atmosphere, containing a pump and an electromagnetic flow meter as shown in Fig. 1. The jet issues at 20 °C from a 17 mm (or 20 mm) nozzle diameter and impinges on the moving surface perpendicularly.

The moving surface is a plastic strip which is stretched between two rollers. It is stretched enough to prevent deformation by the impact of the water jet. The width of the plastic strip is large enough for the jet expansion but water can flow by the sides. This moving strip is driven by an electric motor and its speed is measured by a tachometer.