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An investigation on non-circular hydraulic jumps formed due to obliquely impinging circular liquid jets

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ABSTRACT

Oblique impingement of a circular liquid jet with a horizontal target gives rise to hydraulic jumps of unique no-circular shapes. Hydrodynamics of this phenomenon have been experimentally investigated in the present work. Hydraulic jumps of two broad categories have been observed. At higher angles of jet inclination, the jumps are bounded by a smooth curve. However, at lower angles of inclination, typical jump profiles with corners have been observed. Effect of jet inclination angle on jump the profile and jump area has been investigated. Measurements of stagnation pressure and film thickness for different jet inclination angles and volume flow rates of liquid are reported. Film thickness measurements are made using an innovative cylindrical conductive probe, at the forward ($\theta = \pi$) and backward ($\theta = 0$) radial locations, for regions both before and after the jump. The striking difference between the non-circular and circular hydraulic jumps is also critically assessed.

1. Introduction

Radially-spreading thin liquid film formation due to normal impingement of liquid jets is an established technique for providing high local heat/mass transfer rates between a fluid and a surface in a variety of applications, including glass manufacturing, paper drying, gas turbine cooling, and electronic packaging, to name a few. The stagnation pressure of a high-speed liquid jet significantly raises the saturation temperature and can enable high wall temperatures and consequently, high heat fluxes to exist in the stagnation zone [20]. Both the pressures and heat-transfer coefficients drop rapidly, as the distance from the stagnation point increases.

The circular hydraulic jump [1,5] can be formed as a consequence of normal impingement of a cylindrical liquid jet on a smooth horizontal surface. The liquid spreads out radially along the surface forming a thin film. At some radial distance from the impingement point, also called as stagnation point, the film thickness abruptly increases, characterizing the jump. (Fig. 1) illustrates a circular hydraulic jump formed under these conditions, as observed in our laboratory experiments. The hydraulic jump is termed as 'circular', because of a radially symmetric flow at the jump location. Close to the jet, the fluid layer is thin and the motion is rapid. However, somewhat away from the impingement zone the flow velocities are slower, with a consequent increase in the film thickness. The transition between these two types of motion takes place in a rather abrupt manner, more precisely, over a narrow annular region characterized by a sudden change in flow depth. These kinds of hydraulic jumps involve a strongly distorted free surface, a boundary layer region and a subsequent separation of a flow [31]. Such features have been studied extensively in the past, both theoretically (for instance, in [12,4,14,15] and experimentally (for instance, in [23,16,9,20,7]. Some other investigations have addressed similar problems both theoretically and experimentally, although number of such studies reported has been very few [30,22,11,3,6].

In many industrial applications, the impinging jet is obliquely inclined with the target plate, giving a plethora of interesting fluid flow patterns, most of which might appear to be somewhat intuitive, but are by no means obvious. Oblique impinging jets, as compared to normal impinging jets, have received relatively less attention in fluid mechanics literature. The schematic of a circular liquid jet impinging obliquely on a flat horizontal surface, illustrating the associated flow phenomenon, is depicted in Fig. 2. Following the studies of Beltos [2], Rubel [26,27], Sparrow and Lovell [28] and Tong [29], it can be inferred that the radial spreading flow is, in general, three-dimensional in nature. This is due to the fact that the section of an inclined circular jet on a horizontal plate is nothing but an ellipse. It has also been observed from experimental investigations that under these conditions, the stagnation point shifts further upstream as can be seen from Fig. 2. Fundamentally, hydraulic jumps encountered in a flow due to oblique impinging liquid jets are somewhat different from the circular hydraulic jumps formed due to normal impinging jets on a horizontal surface. Recently, Kate et al. [17] executed a fundamental study to

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Fig. 1. Circular hydraulic jump due to a normal impinging circular liquid jet with a volume flow rate of water, $Q = 1 \times 10^{-4}\ \mathrm{m^3/s}$, nozzle diameter, $d = 8.8$ mm.

obtain valuable physical insights of different types of non-circular hydraulic jumps. These authors predicted radial locations of the jump (jumps formed when the jet inclination angle with horizontal, ϕ, is grater than 25°), as

$$R_j(\phi,\theta) = c\left[\frac{Vr_0^2}{2}\,\frac{\sin^3\phi}{(1+\cos\phi\cos\theta)^2}\right]^{5/8} \nu^{-3/8}\,g^{-1/8} \tag{1}$$

where c is a constant, r_0 is the jet radius, ϕ is the jet inclination angle, θ is the azimuthal location, V is the jet velocity, ν is the kinematic viscosity, and g is the acceleration due to gravity. Their experimental results were in good agreement with the above equation. Kate et al. [18,19] subsequently advanced the above considerations towards elucidating the interactions of hydraulic jumps formed by two normal impinging circular liquid jets and hydraulic jumps with corners due to obliquely inclined circular liquid jets. However, their observations were mostly qualitative in nature, with no detailed quantification of the observed fluid dynamic characteristics. Aim of the present work, accordingly, is to obtain detailed quantitative measurements for deriving more pin pointed information on hydraulic jump characteristics observed under conditions similar to the ones reported in the above-mentioned study. In particular, special emphasis is given to obtain the area of the thin liquid film bounded by the jump, film thickness and the stagnation pressure, as a parametric function of the angle of jet obliquity. Detailed investigations in this regard are summarized in the subsequent sections.

2. Experiments

2.1. Experimental facility

A schematic diagram of the experimental facility is shown in Fig. 3. It consists of a closed-loop water jet system. A centrifugal pump (0.5 HP, head 30/6 m, capacity 15/40 lpm, 2800 rpm) is used for delivering filtered water in the form of a jet at the required flow rate. The flow rate is measured using two rotameters calibrated in the range of 1–10 lpm and 1–20 lpm. The rotameter is connected to a nozzle arrangement through the PVC piping. Circular tubes of brass and stainless steel, in the diameter range 4–10 mm, are used as nozzles. These tubes have length to diameter ratio of 150–200,

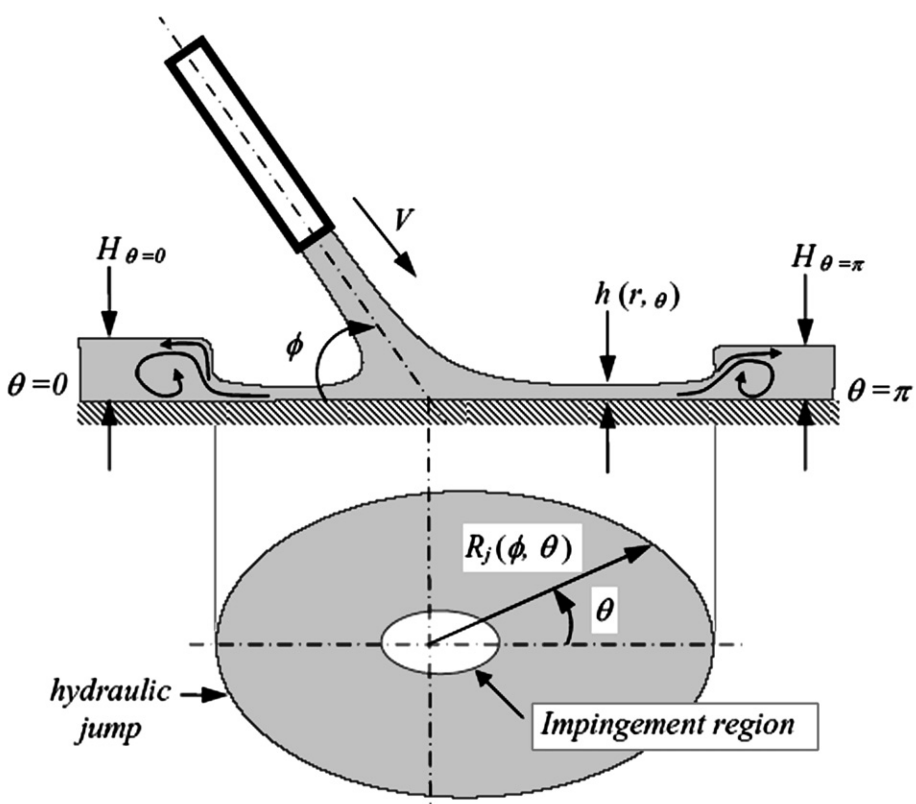

Fig. 2. A schematic diagram of an oblique impinging jet and the consequent non-circular hydraulic jump.