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The influence of nozzle diameter on the circular hydraulic jump of liquid jet impingement

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ABSTRACT

In this study, the circular hydraulic jump of jet impingement cooling was experimentally investigated using water as the test fluid. The effects of nozzle diameter (0.381, 0.506, 1, 2, 3.9, 6.7, 8 mm) on the hydraulic jump radius were considered. The results indicate that the dimensionless hydraulic jump radius (r_{hj}/d) is independent of the nozzle diameter under fixed impingement power conditions, while the dimensionless hydraulic jump radius increases with decreasing nozzle diameter under fixed jet Reynolds number conditions. Based on the experimental results, a new correlation for the hydraulic jump radius is proposed as a function of the impingement power alone. It is shown that the proposed empirical correlation for the dimensionless hydraulic jump radius has the same form as that derived from a dimensional analysis of the conservation equations. In addition, the results clearly show that the dimensionless hydraulic jump radius depends on two dimensionless groups, jet Reynolds and Froude numbers, rather than just one, jet Reynolds number.

1. Introduction

A hydraulic jump is a hydraulic phenomenon which is frequently observed in rivers and canals, industrial applications, and manufacturing processes, as well as in kitchen sinks. The phenomenon is dependent mainly upon the initial liquid speed. If the initial speed of the liquid is below the critical speed, then no jump is possible. For initial flow speeds which are above the critical speed, a hydraulic jump occurs. When a water jet impinges on a horizontal plate, a circular hydraulic jump can form some distance away from the jet impact point. The determination of the hydraulic jump radius is very important since the heat transfer characteristics of impinging jets are drastically changed at the location of the hydraulic jump, as mentioned by previous researchers [19,2,14,4,5]. Due to the importance of the hydraulic jump, extensive studies on the heat transfer and hydrodynamics of hydraulic jumps have been reported in the literature [3,6,10,21,9,23,15,16].

Stevens and Webb [19] studied the flow structure of a water film formed by a circular jet impinging perpendicularly on a horizontal surface. The experimental study was performed for nozzle diameters in the range of 2.2–8.9 mm and jet Reynolds number in the range of 1000–52,000. The dimensionless hydraulic jump radius was suggested to be a function of jet Reynolds number: $r_{hj}/d = 0.0061Re^{0.82}$, where d is the nozzle diameter. Baonga et al. [2] conducted an experimental study on the hydrodynamic and thermal characteristics of a free liquid jet impinging on a heated disk. They performed experiments for nozzle diameters of 2.2 and 4 mm and jet Reynolds numbers in the range of 600–9000. An empirical correlation for the dimensionless hydraulic jump radius was suggested as a function of jet Reynolds number: $r_{hj}/d = 0.046Re^{0.62}$. Liu and Lienhard [14] performed an experimental study for a nozzle diameter of 4.96 mm. The effects of jet Reynolds number, jump Weber number, and jet Froude number on the dimensionless hydraulic jump radius were investigated. Even though much data has been obtained by previous researchers, the effect of jet Froude number by the variation of nozzle diameter has not been taken into account in the previous studies. Fig. 1 shows the hydraulic jump for 2 mm and 0.506 mm inner diameter nozzles.

The objective of the current research is to determine the effect of nozzle diameter on the hydraulic jump radius for impinging jets under a fixed jet Reynolds number and impingement power conditions. A wide range of nozzle diameters (0.381, 0.506, 1, 2, 3.9, 6.7, 8 mm) were considered using water as the test fluid. Based on these experimental results, a new correlation for the dimensionless hydraulic jump radius (r_{hj}/d) is developed solely as a function of a dimensionless impingement power, $I_p^* = \frac{\pi}{8}\left(\frac{u^3 d^2}{\nu^{7/3} g^{1/3}}\right)$.

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Nomenclature

d	nozzle diameter
Fr	jet Froude number
g	gravitational acceleration
h	height of the fluid
I_p^*	dimensionless impingement power
ΔP	pressure drop
Q	flow rate
r	lateral distance from stagnation point
r^*	dimensionless lateral distance from stagnation point
r_{hj}	hydraulic jump radius
Re	jet Reynolds number
u	jet velocity
u_r^*	dimensionless radial velocity
u_z^*	dimensionless vertical velocity
z	vertical distance from stagnation point
z^*	dimensionless vertical distance from stagnation point
Greek symbol	
ν	dynamic fluid viscosity
ρ	fluid density

2. Experimental procedures

A schematic diagram of the experimental apparatus for impinging water jets is shown in Fig. 2. The water jets vertically impinges on a plate. The water flow was supplied by a reservoir to ensure a steady flow. A pneumatic air pump was used to control the liquid flow rate. A coriolis flowmeter (Micro motion Inc.) was used to measure liquid flow rates and liquid density, both measured with an accuracy of 0.1%. The jet velocity can be readily found from the mass flow rate and the jet diameter. The circular pipe nozzle was fixed on a 3 axis (x–y–z) stage (Thorlabs, Inc) with 10 μm resolution. Thus, the nozzle could be moved either parallel or perpendicular to the direction of the jet.

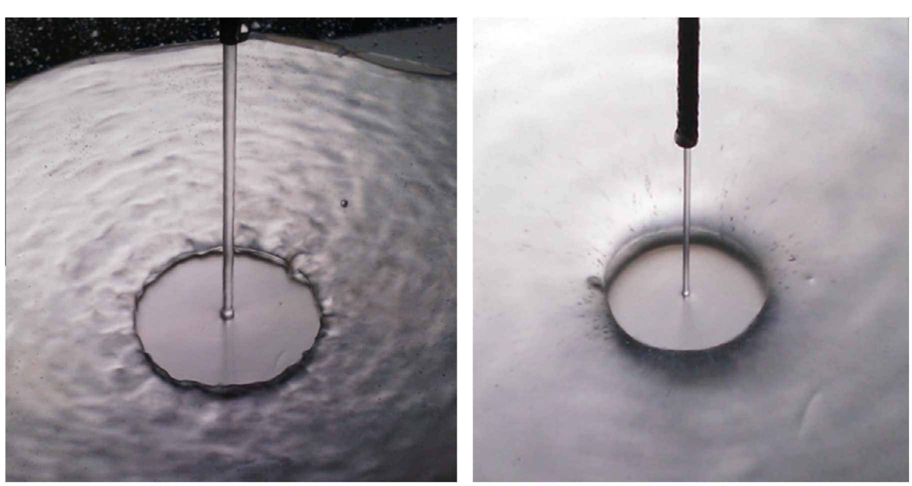
Seven circular, stainless-steel nozzles were used in the experiment. The nozzles had inner diameters of 0.381, 0.506, 1, 2, 3.9, 6.7, and 8 mm. All of the nozzles in the experiment are straight tubes. The length of the nozzle is 60 times the nozzle inner diameter to ensure a fully developed flow. The inner diameter of each micro-nozzle (0.381, 0.506, and 1 mm) was measured using a scanning electron microscope (SEM).

The impingement surface was elevated above the remainder of the test section. Thus, as the wall jets fell off the impingement surface into the pool, the jet impingement was not influenced by the downstream conditions. The impingement plates were made of stainless steel with the diameters of 2 cm for 0.381 and 0.506 mm nozzles, 10 cm for 1 and 2 mm nozzles, and 60 cm for 3.9, 6.7, and 8 mm nozzles. It was verified that the results were independent of plate diameter when the plates were larger than 20 times the nozzle diameter. In order to ignore the velocity difference due to gravity between the jet velocity at impingement point and the jet velocity at nozzle exit, the nozzle-to-plate spacings of 2 nozzle diameter for 3.9–8 mm nozzles and 40 nozzle diameter for 0.381–2 mm nozzles were used, respectively. Therefore, the jet diameter at the impingement plate and nozzle diameter are same. The water temperature at the nozzle exit was fixed at 20 °C. The variation of impinged water temperature was not included in the present study. Photographs were used to measure the hydraulic jump radius as shown in Fig. 1. Ten measurements of the hydraulic jump radius were obtained from photographs by using a digital camera (Nikon, D50) and a pulse generator (EG&G Electro-optics, LS-1130-1) [7,8]. The uncertainty in the hydraulic jump radius is estimated with a 95 percent confidence level using the methods suggested by Kline and McKlintock [13] to be 5.2%.

3. Results and discussion

3.1. Validation

The experimental data of the present study for a dimensionless hydraulic jump radius were compared with the empirical correlation of Stevens and Webb [19] as a validation process. The dimensionless hydraulic jump radius for 2.0 mm and 3.9 mm nozzles for jet Reynolds numbers between 3500 and 15,000 were examined. The current data agrees with the empirical correlation of Stevens and Webb ($r_{hj}/d = 0.0061Re^{0.82}$) within ±20% (Fig. 3).



(a) (b)

Fig. 1. Hydraulic jump for an impinging jet: (a) d = 2.0 mm with r_{hj} = 16.57 mm (b) d = 0.506 mm r_{hj} = 6.39 mm.