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Experimental study of the hydrodynamic and heat transfer of air-assistant circular water jet impinging a flat circular disk

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ABSTRACT

Hydrodynamic and heat transfer characteristics of the circular hydraulic jump by air-assistant water jet impingement was experimentally investigated using water and air as the test fluid. The effects of volumetric quality ($\beta = 0$–0.9) on the hydraulic jump radius, local Nusselt number and, pressure at the stagnation point were considered under fixed water-flow-rate condition. The results showed that the dimensionless hydraulic jump radius increased with volumetric quality, attained a maximum value at around 0.8 of the volumetric quality, and then decreased. The hydraulic jump of two phase impinging jet is governed by the stagnation pressure and the lateral variation of Nusselt number is governed by hydraulic jump radius. Based on the experimental results, a new correlation for the normalized hydraulic jump radius of the impinging jet are developed as a function of the normalized stagnation pressure alone.

1. Introduction

A hydraulic jump is a hydraulic phenomenon which is frequently observed in rivers and canals, industrial applications and manufacturing processes. When liquid at high velocity discharges into a zone of lower velocity, a rather abrupt rise occurs in the liquid surface. The phenomenon is dependent mainly upon the initial fluid speed. If the initial speed of the fluid is below the critical speed, then no jump is possible. For initial flow speeds which are above the critical speed, the hydraulic jump occurs. When a water jet impinges on a horizontal plate, a circular hydraulic jump forms 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 hydraulic jump, as mentioned by previous researchers (Stevens and Webb [1]; Baonga et al. [2]; Liu and Lienhard [3]). Due to the importance of hydraulic jump, extensive studies on the heat transfer and hydrodynamics of hydraulic jumps for single-phase impinging jets have been reported in the literature (Chanson [4]; Godwin [5]; Louahlia-Gualous and Baonga [6]; Watson [7]; Craik et al. [8]; Zhao and Khayat [9]; Mikielewicz and Mikielewicz [10]; Vishwanath et al. [19]).

Stevens and Webb [1] studied the flow structure of a water film formed by a single-phase 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 Reynolds number in the range of 1000–52,000. The dimensionless hydraulic jump radius was suggested to be a function of Reynolds number: $r_{hj}/d = 0.0061\mathrm{Re}^{0.82}$. Baonga et al. [2] conducted an experimental study on the hydrodynamic and thermal characteristics of a free liquid single-phase jet impinging on a heated disk. They performed experiments for nozzle diameters of 2.2 and 4 mm and Reynolds numbers in the range of 600–9000. An empirical correlation for the dimensionless hydraulic jump radius was suggested as a function of Reynolds number: $r_{hj}/d = 0.046\mathrm{Re}^{0.62}$. Liu and Lienhard [3] performed an experimental study for a nozzle diameter of 4.96 mm. The effects of Reynolds number, Weber number, and Froude number on the dimensionless hydraulic jump radius of single-phase impinging jet were investigated. Vishwanath et al. [19] investigated a study for the effect of initial momentum flux on the circular hydraulic jump at low Reynolds numbers in the range of 150–1000. They showed that the momentum flux is an additional controlling parameter in determining the jump location. Choo and Kim [11] conducted an experimental study for the effect of nozzle diameter on hydraulic jump radius. They showed that dimensionless hydraulic jump radius 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.

Injection of air into a liquid jet flow before it exits the nozzle, forming an air-assisted impinging jet, can provide a large heat transfer enhancement. Recently, several researchers have observed heat transfer enhancement resulting from the addition of a gas (or

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Nomenclature

d	nozzle diameter [m]
d_{hj}	hydraulic jump diameter [m]
d_{hj}/d	dimensionless hydraulic jump diameter [–]
Nu_r	lateral variation of Nusselt number [–]
P_{stag}	pressure measured at stagnation point [kPa]
Q_w	water flow rate [m^3/s]
Q_a	air flow rate [m^3/s]
Q_{tot}	total flow rate [m^3/s]
Re	jet Reynolds number [ud/ν]
r	lateral distance from stagnation point [m]
r_{hj}	radius measured from jet stagnation point [m]

Greek symbol

β	volumetric fraction, ($Q_a/Q_w + Q_a$) [–]

Subscripts

hj	hydraulic jump
stag	stagnation point
w	water

Superscripts

$*$	normalization

vapor) phase to an impinging liquid jet. Serizawa et al. [12] experimentally studied the heat transfer characteristics of an impinging circular jet of an air–water mixture for Reynolds numbers in the range $25{,}000 < Re_w < 125{,}000$. Heat transfer coefficient was increased by a factor of 2 at a volumetric fraction value of 0.53. Chang et al. [13] experimentally investigated the heat transfer characteristics of confined impinging jets using Freon R-113. Relative to a single-phase jet, heat transfer of the liquid–vapor jets was enhanced by a factor of 1.2. Zumbrunnen and Balasubramanian [14] measured convection heat transfer enhancement caused by air bubbles injected into a planar water jet. Over the range of liquid-only Reynolds number of $3700 \leqslant Re_w \leqslant 21{,}000$ and the volumetric fraction between $0 \leqslant \beta \leqslant 0.86$, heat transfer was increased by as much as a factor of 2.2 at the stagnation point. Hall et al. [15] performed an experimental study of boiling heat transfer for air–water impinging jets. For the volumetric fraction ranging from 0 to 0.4 and the liquid-only Reynolds number of $11{,}300 \leqslant Re_w \leqslant 22{,}600$, heat transfer increased by as much as a factor of 2.1 at the stagnation point. Choo and Kim [16,17] observed the heat transfer effects of an air-assisted impinging jet and obtained an optimum point under a fixed pumping power condition. Trainer et al. [18] investigated nozzle diameter effect on heat transfer characteristic of the impinging jet and show that heat transfer of the air-assisted jets was enhanced by a factor of 2.6. Even though many data have been obtained by previous researchers for single phase and two phase impinging jets, the effect of volumetric quality on the hydraulic jump radius was not yet presented for two phase impinging jets.

The purpose of the current research is to determine the effect of changing volumetric quality of a constant flow rate on the hydraulic jump radius and local Nusselt number for impinging jets. The working fluids are air and water. The single phase, or water only, is crucial for use as a reference and validation of the experiment. Four different Re of water (3030, 3463, 3,896, and 4329) are tested as each of the volumetric qualities increase from $\beta = 0$–0.9. Based on these experimental results, a new correlation for the dimensionless hydraulic jump radius (d_{hj}/d) was developed as a function of normalized stagnation pressure (P^*_{stag}) alone.

2. Experimental procedures

Fig. 1 shows a schematic diagram of the experimental apparatus. Compressed air and water passed through flexible tubing before entering the two-phase mixer. The airflow was supplied by a high-pressure tank to ensure a very clean and steady flow. The flow was then regulated and controlled by a mass flow controller (Omega FMA5520A) having an accuracy level of ±1% and a repeatability of ±0.15%. The full-scale range of the mass flow controller was 10 standard liters per minute. Water was used as the working liquid. A commercial water line was used to supply the water. The liquid flow was regulated and controlled by valve operated flowmeters (Dwyer RMC-135-SSV and Dwyer RMB-82D-SSV). The liquid passed through flexible tubing before entering a two phase mixture.

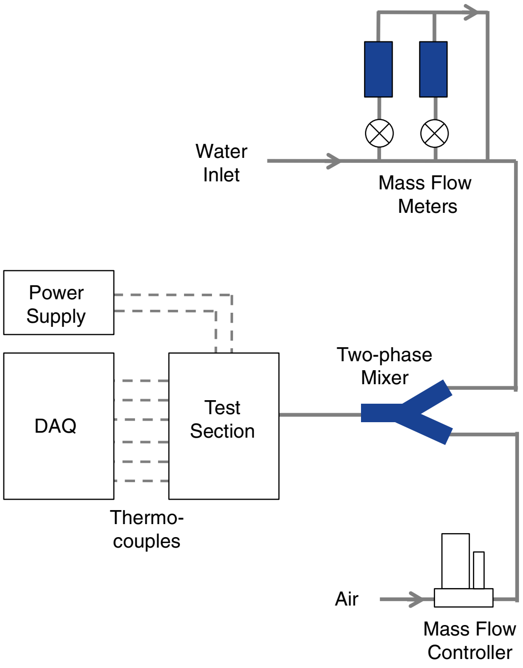

Fig. 1. Schematic diagram of experimental set-up.

A circular, extruded acrylic nozzle was used in the experiment after the two phase mixer. The nozzle acted as the nozzle which produced the impinging jet. It was 470 mm long with a 5.86 mm inner diameter. The nozzle in the experiment is a straight tube. The length of the nozzle is 80 times the nozzle inner diameters to ensure a fully developed flow. The circular nozzle was fixed on a 3-axis (x–y–z) stage with a 10 μm resolution, (Thorlabs, Inc, PT3A/M). The nozzle exit was positioned 5.86 mm above the impinging surface to give an $h/d = 1$. Manometers (Dwyer Series 490A and Meriam M200-DI001) were used to measure the wide range of pressures from the impinging jet's stagnation zone. The manometers have the range of 0–30 kPa and 0–6.89 kPa with accuracies of ±0.5% and ±0.05%, respectively. stagnation pressure of the