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The effect of volumetric quality on heat transfer and fluid flow characteristics of air-assistant jet impingement

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ABSTRACT

Heat transfer characteristics of air-assistant water jet impingement was experimentally investigated under a fixed water flow rate condition. Water and air were used as the test fluids. The effects of volumetric quality (β = 0–0.9) on the Nusselt number and pressure were considered. The results showed that the stagnation Nusselt number increased with volumetric quality, attained a maximum value at around 0.8 of the volumetric quality, and then decreased. The stagnation Nusselt number of the air-assistant water jet impingement is governed by the stagnation pressure. Based on the experimental results, a new correlation for the normalized stagnation Nusselt number is developed as a function of the normalized stagnation pressure alone. In addition, the lateral variation of Nusselt number is governed by hydraulic jump radius.

1. Introduction

Impinging jets are widely used in many engineering applications for the heating, cooling, and drying of surfaces as they offer high rates of heating, cooling, and drying. Major industrial applications for impinging jets include turbine blade cooling, electronic equipment cooling, metal annealing, and textile drying. Due to this diverse range of uses, many investigations have examined the heat transfer characteristics of impinging jets in the past decades [1–22].

Several researchers have observed heat transfer enhancement resulting from the addition of a gas (or vapor) phase to an impinging liquid jet. Trainer et al. [23] 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. Hall et al. [24] 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. Zumbrunnen and Balasubramanian [25] 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. Serizawa et al. [26] 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. [27] 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. Choo and Kim [28] observed the heat transfer effects of an air-assisted impinging jet and obtained an optimum point under a fixed pumping power condition. In addition, 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 [33–37]. 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 [29,38–47]. 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. Even though many data have been obtained by previous researchers for two phase impinging jets, the effect of volumetric quality on

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Nomenclature

d	nozzle diameter [m]
d_{hj}	hydraulic jump diameter [m]
d_{hj}/d	dimensionless hydraulic jump diameter [–]
g	gravitational acceleration [m/s^2]
H	nozzle-to-plate spacing [m]
Nu_r	lateral variation of Nusselt number [–]
Nu_w	Nusselt number of water jet at stagnation point [–]
Nu_{tp}	Nusselt number of two-phase jet at stagnation point [–]
Nu^*_{tp}	normalized Nusselt number at stagnation point, (Nu_{tp}/Nu_w) [–]
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]
Re_w	Reynolds number for water [–]
r	lateral distance from stagnation point [m]
r_{hj}	radius measured from jet stagnation point [m]
u	jet velocity [m/s]

Greek symbol

ρ	density of water jet [kg/m^3]
β	volumetric fraction, ($Q_a/Q_w + Q_a$) [–]

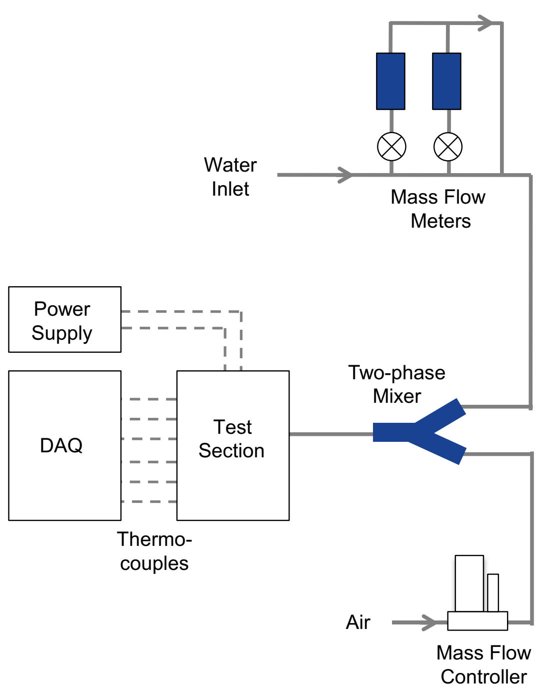

Fig. 1. Schematic diagram of experimental set-up.

the relationship of Nusselt number, hydraulic jump, and stagnation pressure are not yet presented for two-phase impinging jets.

The purpose of this study is to determine the relationship of Nusselt number, hydraulic jump, and stagnation pressure for two-phase impinging jets. The hydraulic jump diameter and stagnation pressure were measured to understand how those affect heat transfer characteristics. Based on the experimental results, a new correlation for the normalized stagnation Nusselt number is developed as a function of the normalized stagnation pressure alone. In addition, it is found that the lateral variation of Nusselt number is governed by hydraulic jump size.

2. Experimental procedures

Fig. 1 shows a schematic diagram of the experimental apparatus. The jets vertically impinges on a plate. 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.

A rigid circular, extruded acrylic tubing was used in the experiment after the two phase mixer. At the end of the tubing was 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. The stagnation pressure of the impinging jet was measured between the stagnation zone and the atmospheric pressure.

A schematic of the test section is presented in Fig. 2. The test section was constructed out of clear acrylic sheet. The DC power supply was connected to the bus bar soldered to the heater at the center of the impingement surface. The heater is made of stainless steel that is 0.0508 mm thick, 12.5 mm wide and 192.8 mm

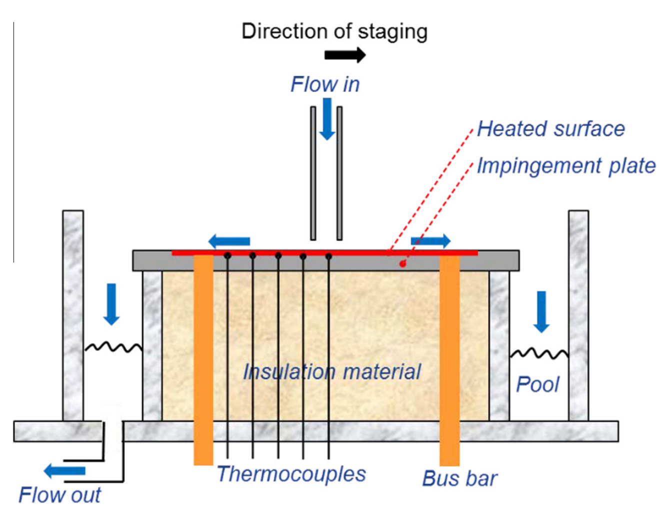

Fig. 2. Test section configuration.