Non-Contact Measurements of Water Jet Spreading Width with a Laser Instrument (Postprint)

Authors: Funami, Y.„ Hasuya, R.„ Tanabe, K., Nakanishi, Y.

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Abstract

Jet spreading width is one of the important characteristics of water jets discharging into the air. Many researchers have dealt with measuring this width, and contact measuring methods on the water jet surface were employed in a lot of the cases. In order to avoid undesirable effects caused by the contact on the jet surface, we introduce non-contact measuring methods with a laser instrument to the measurements of jet spreading width. In measurements, a transmitter emits sheet-like laser beam to a receiver. The water jet between the transmitter and the receiver interrupts the laser beam and makes a shadow. The minimum and maximum values of the shadow width are measured. In addition, pictures of the water jet are taken with a scale, and the shadow width is measured from the pictures. The experiments on various needle strokes were performed. Three kinds of width consistent with the jet structure were obtained. In the results, it can be concluded that our non-contact measuring methods are feasible. The data of jet spreading widths and jet taper were obtained and are useful for future applications.

Full Text

Preamble

Jet spreading width is one of the important characteristics of water jets discharging into the air. Many researchers have measured this width using contact methods that physically touch the water jet surface. To avoid undesirable effects caused by such contact, we introduce non-contact measuring methods using a laser instrument. In these measurements, a transmitter emits a sheet-like laser beam to a receiver. The water jet between them interrupts the beam and creates a shadow, from which we measure the minimum and maximum shadow width values. Additionally, we photograph the water jet with a scale and measure the shadow width from these images. Experiments were performed at various needle strokes, yielding three kinds of width consistent with the jet structure.

The results demonstrate that our non-contact measuring methods are feasible, providing useful data on jet spreading widths and jet taper for future applications.

Keywords: Water jet, Jet spreading width, Jet taper, Non-contact measurement, Laser instrument

Introduction

Understanding the physics of water jets discharging into air is crucial for engineering applications such as fire-fighting equipment, cutting machines, and impulse turbines. Consequently, many researchers have intensively studied water jets.

Hoyt et al. investigated water jets using special photography techniques, focusing on laminar-turbulent transition and droplet formation [1-4]. They also examined polymer solution jets, finding that polymers reduced small-scale disturbances on the jet surface. Yanaida researched high-speed water jets, determining jet spreading width using an electric measuring method [5]. He found that jet spreading width does not depend on pressure or fluid type, but is proportional to the square root of distance from the nozzle exit, with the proportional constant affected by nozzle shape. Brekke examined velocity distribution in water jets for Pelton turbine applications, using a nozzle with 2 or 6 fins connected to a bend pipe and measuring velocity with a miniature Pitot tube just downstream of the nozzle [6]. Zhang et al. developed a laser Doppler anemometry (LDA) method to investigate water jets, using both straight and 90-degree bend pipes and demonstrating that bends strongly affect jet flow [7, 8].

These previous works employed various contact measuring methods to obtain flow characteristics. Pitot tubes penetrated the water jet, electric probes touched the jet surface, and LDA methods required an optical wedge to contact the surface to ensure laser beam transmission. Such contact inevitably affects flow characteristics undesirably.

While water jets have many important characteristics, this paper focuses on jet spreading width. We employ non-contact measuring techniques using a laser instrument to avoid undesirable contact effects. Recognizing that water jet surface motion is unstable and unsteady (as visible in Hoyt' s photographs [1-4]), we consider this instability and assume a water jet can be divided into three regions: core, intermittent, and spray. Our measuring techniques account for this structure.

The objective is to examine the feasibility of our measuring techniques and obtain jet spreading width data for future applications.

Water Jet Structure

The water jet surface changes unsteadily due to turbulence and hydrodynamic instabilities. Hoyt et al. observed instability waves, air entrainment, and droplet generation [1-4]. Figure 1 [Figure 1: see original paper] shows a water jet from our experiment, revealing unsteady surface motion, wavy shape, and abundant droplets. Considering these unsteady motions, we assume the jet structure shown in Figure 2 [Figure 2: see original paper].

The core region is defined as the stable standing region, the intermittent region is where the unsteady wavy surface passes, and the spray region contains droplets. We measure the width of each region in our experiments.

Experiments

Apparatus

Figure 3 [Figure 3: see original paper] shows the experimental apparatus schematic, identical to that used for stationary Pelton bucket experiments [9]. The maximum water head is 28.5 meters. Flow rate is measured with an ultrasonic flow meter and pressure with a pressure transducer, both located upstream of the nozzle. Jet spreading width is determined with a laser dimension measuring instrument (details described below). We photograph the water jet from the front using a digital camera with lighting equipment.

A needle in the nozzle adjusts flow rate. The nozzle internal structure is shown in Figure 4 [Figure 4: see original paper]. The needle is supported by ribs, a common design in impulse turbines. Needle stroke (Sn) is defined as the stroke from the needle location when the nozzle is completely closed. Jet spreading widths are measured normal to the surface made by the ribs, which corresponds to the laser beam direction.

Jet Spreading Width Measurement

Jet spreading width is measured using a non-contact technique: laser dimension measurement. We use a high-speed laser scan micrometer (LS-5040, KEYENCE) with specifications shown in Table 1 . The micrometer consists of a transmitter and receiver. The transmitter emits a sheet-like laser beam that the receiver detects. A water jet is positioned between them, interrupting the beam and creating a shadow on the receiver (Figure 5 [Figure 5: see original paper]). This width measurement is called "DIA mode."

Because a water jet surface is wavy and generates droplets, the measured shadow width may vary instantaneously. Therefore, we employ two measurement modes. "Bottom-hold mode" records the minimum shadow width over a set duration, which correlates with the core region width at a given axial position. "Peak-hold mode" records the maximum width, which is greatly affected by droplets and represents the spray region width. We use both modes simultaneously, recording both minimum and maximum values over a 10-second duration. The instrument' s accuracy is confirmed by measuring a precisely finished 30-mm diameter calibration cylinder before and after experiments.

We also photograph water jets with a scale in a blackout-curtained room, using only the laser scan micrometer transmitter. The jet is set up between the transmitter and scale, and we measure the shadow width on the scale from pictures (Figure 6 [Figure 6: see original paper]). We use a Nikon D7200 digital single-lens reflex camera with an AF-S DX NIKKOR 16-80mm f/2.8-4E ED VR lens featuring Nano Crystal Coat to reduce ghosting and flare. Camera settings are shown in Table 2 . If exposure time were shorter than the laser scan time (the inverse of scan rate), the laser beam would not appear in the image. Therefore, exposure time must be sufficiently longer, meaning the photographed laser beam is integrated over time. The shadow width in the picture thus represents the averaged interruption width, approximating the intermittent region width.

Experimental Conditions

In all experiments, the total water jet head (H) is set to 21 m. Three needles of different lengths are used with strokes of 14, 9, and 4 mm. The relationship between needle stroke (Sn) and flow rate (Q) is shown in Figure 7 [Figure 7: see original paper].

The measurement range extends from x = 0 mm to x = 100 mm along the jet axis, with the origin at the needle tip. The positive x-direction corresponds to flow direction. Measuring point intervals are 2 mm between x = 0-20 mm and 10 mm between x = 20-100 mm. At each point, we perform 25 measurements with the laser scan micrometer in both bottom-hold and peak-hold modes, and 20 photographic measurements.

Results

Scatters of Jet Spreading Widths in a Typical Experiment

Figure 8 [Figure 8: see original paper] shows results from a typical experiment with needle stroke set to 14 mm. Symbols represent measured jet spreading widths (W) non-dimensionalized by the nozzle exit width (W0), calculated using Bernoulli' s principle and continuity. At each measuring point, 25 symbols appear for core and spray region widths, and 20 for intermittent region width, corresponding to the number of measurements. Lines connect averaged values at each point.

In all regions, data scatter is small upstream but relatively large downstream. Spray region width shows the largest scatter, while core region width shows the smallest, consistent with visual observations and the unstable, unsteady nature of water jets.

Averaged Values of Jet Spreading Widths

Three experiments were performed for each needle stroke setting. Figure 9 [Figure 9: see original paper] shows results for Sn = 14 mm, with symbols representing averaged values from each experiment. The averaged W0 values from all experiments are listed in Table 3 . Lines connect values obtained by averaging the three symbols at each measuring point.

The magnitude relationship between the three region widths is consistent with the assumed jet structure in Figure 2 [Figure 2: see original paper]: spray region width > intermittent region width > core region width. The non-dimensional widths (W/W0) of all three regions decrease with non-dimensional axial position (x/W0) near the nozzle exit. After passing the inflection point, W/W0 increases, with the spray region showing the highest growth rate and the core region the lowest.

Figures 10 [Figure 10: see original paper] and 11 [Figure 11: see original paper] show results for Sn = 9 mm and Sn = 4 mm, respectively. These exhibit similar tendencies, though for Sn = 4 mm, the core region width decreases almost monotonically with increasing x/W0, likely because the flow rate is very low (Figure 7 [Figure 7: see original paper]). Across all cases, widths in the three regions decrease with decreasing needle stroke (i.e., decreasing flow rate).

Effect of Needle Stroke on Jet Taper

Jet taper—the increment ratio of jet width in the flow direction—is another important characteristic, particularly for impulse turbine engineers [10]. In almost all our results, inflection points occur between x/W0 = 0 and x/W0 = 2. Therefore, we calculate jet tapers using data between x/W0 = 2 and x/W0 = 6, after passing these inflection points. In this range, we fit width data for each region to a line using least squares; the slope (W/ x) is the jet taper.

Figure 12 [Figure 12: see original paper] shows the jet tapers from our experiments. Except for the intermittent region, jet tapers increase with needle stroke. The intermittent region shows the largest jet taper for Sn = 9 mm. Only the core region jet taper for Sn = 4 mm has a negative value.

Conclusions

Non-contact measuring methods using a laser instrument were introduced to obtain jet spreading width data—one of the important characteristics of water jets. Experiments at various needle strokes yielded results consistent with water jet structure, demonstrating that our non-contact methods are feasible for obtaining jet spreading widths.

We obtained jet spreading width and jet taper data for various needle strokes, which are useful for future applications such as impulse turbine design. While much research including ours has been conducted, the physics of water jets discharging into air remains inadequately understood. In particular, knowledge about nozzle condition effects (shape, internal structure, inlet bend) on jet flow is insufficient. Studying these effects with our measuring methods represents future work.

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Note: Figure translations are in progress. See original paper for figures.