Flume Experiments on the Oscillating Wall Jet Induced by the Swing Oblique Impingement Jet

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Abstract. The flow characteristics of oscillating wall jets induced by swinging an oblique impingement jet in a rectangular flume is experimentally investigated. By using ultrasonic Doppler velocity profiler (UDVP), the phase-dependent velocity profiles, the phase-varying turbulence fluctuations, and the decay of the velocity along the downstream surface of the oscillating wall jets are observed in a two-dimensional plane. Results show that the mean velocity profile of the oscillating wall jet in the near-bed region generally follows the Weibull distribution, similar to the steady wall jet. Greater fluctuation magnitudes are produced by the oscillating wall jet at the low-speed provocation and high-speed suppression phases than that at the accelerating and decelerating phases. The velocity fluctuations increase with the increasing oscillating frequency. Both the oscillation offset and amplitude of the oscillating wall jet decay continuously with the spreading distance. The decay rate of oscillation offset along the downstream wall of the oscillating wall jet is higher than the velocity decay rate of steady wall jet, and slightly increases with the increment of the oscillating frequency. The oscillating amplitude decays exponentially with the downstream distance.

1. Introduction
The wall jet induced by the submerged oblique jet impinging on the bed is common in nature and in hydraulic engineering applications. It leads to quantities of investigations on the flow structures of the impingement-induced wall jet, containing the time-averaged velocity profiles [1-3], the turbulence characteristics [4, 5] and velocity decay on the downstream wall [2, 6].

When the submerged oblique jet impinging on the plane, the flow rapidly separates at the stagnation point and generously spreads in the direction of the jet centerline stretching [7]. Due to the mighty adsorption force [8], the wall jet is generated in the near bed region from the stagnation point to a relative certain downstream distance [9]. The near bed region of this wall jet flow theoretically follows the boundary layer flow [8], and the velocity profile within the boundary layer obeys the semilogarithmic wall law, i.e. the velocity increases sharply with the vertical distance y from the bed, and achieves the maximum value at the boundary layer thickness y = δ [1, 2]. During the evolution of the wall jet on the submerged plane, the wall jet can cause large-scale disturbances with greater magnitude in the outer layer and small-scale disturbances close to the wall [3]. The outer-layer turbulent fluctuations involve unsteady momentum exchanges and vortices spiraling towards the centers [3, 4], while the inner-layer...
turbulence is dependent on the skin friction coefficients involving the roughness of the bed surface [5]. When the velocity fluctuation is assumed negligible, the velocity profile of the wall jet is found self-similar and obeys the Weibull distribution during its evolution along the downstream wall [3].

The flow characteristics of the impingement-induced wall jets depends on the initial conditions of the inflowing jet, containing the jet outlet velocity \( u_0 \), the oblique angle (to the surface) \( \theta \) [1, 3] and the distance from the jet outlet to the surface \( H \). The jet outlet velocity \( u_0 \) together with the vertical distance \( H \) was regarded proportionally affects the maximum velocity of the wall jet [2, 5]. Whereas the oblique angle \( \theta \) is generally considered as a significant indicator of the flux separated to each radial direction after the jet impinges on the bed. The separated flux to downstream direction increases with the decreasing oblique angle (to the surface), and the deflected jet was hardly any backward flow when the oblique angle up to \( \theta = 40^\circ-45^\circ \) [1, 3, 9]. During the downstream transportation of the wall jet along the surface, the boundary layer thickness is gradually thicker [1], and the axial jet centerline velocity firstly increases rapidly from the stagnate point to a maximum value and then exponentially decays [2,6,9]. However, jet flow was found randomly oscillating during its impingement on the bed, resulting in unstable flow field on the downstream bed. Gaps still exists in understanding these unstable flow field induced by the oscillation.

Based on these previous achievements, this study further experimentally observed the flow features of the oscillating wall jet induced by the swinging oblique impingement jet in a laboratory flume. The emphasis is to investigate the temporal variation of the flow field for the oscillating wall jet, and the effects of the oscillating frequencies on its flow characteristics. The ultrasonic Doppler velocity profiler (UDVP) is applied to detect the time-varying flow velocity. The swinging oblique impingement jets are performed for the initial oblique angle of \( \theta=45^\circ \), the pendulum angles of \( \alpha=\pm5^\circ \), and ten different swing frequencies \( f = 0-1.33 \text{ Hz} \). Results of the velocity profiles, turbulence characteristics and velocity decay along the downstream bed of the oscillating wall jets are detailed and discussed.

2. Experiments

The experiments were conducted in a circulating two-layer flume in Shanghai Jiao Tong University, which was 11 m long, 1 m wide, and 1 m deep as shown in Figure 1. All the tests were conducted in clear water scour conditions with the submerged water depth preset as \( H_t = 250 \text{ mm} \). The experimental schematic diagram with the coordinate system and variables of an oscillating wall jet is shown in Figure 1. As shown in Figure 1, the measurements were conducted in a two-dimension plane of the jet centerline, \( X \) points to the downstream of the jet flow, and \( Y \) is the vertical direction of the bed.

![Figure 1. Schematic diagram of experimental setup.](image-url)
By swinging the oblique nozzle, the jet flow impinged periodically on the bed, resulting in an oscillating wall-jet flow downstream on the bed surface. The swinging jet system consisted of a jet-flow power source unit, a flow-rate control unit, and a swing execution unit, as shown in Figure 1. The jet-flow power source was a submersible pump, supplying the maximum water-pressure of 1.2 MPa, and the maximum flow-rate of 15 m³/h. The pump was placed 6 m from the observation area to avoid the pump installation disturbance to the flow in observation area. The flow rate control unit contained two valves with the help of the electromagnetic flowmeter, to adjust the jet discharge. The swing execution unit consisted of a fixed plate bracket, a motor, a crank slider mechanism, a moving slide rail and a jet nozzle. The jet nozzle was adopted by a PVC pipe with diameter of D = 50 mm and a length of 400 mm, placed at the vertical distance between the jet exit and plane H/D = 4. The jet nozzle was swung by the motor within an amplitude range of α = ±5°, with the initial oblique angle of θ = 45° to the surface. The frequencies of the swinging jet were controlled in the range of f = 0-1.33 Hz. The detailed experimental parameters are listed in Table 1.

| Run | D (mm) | θ (°) | α (°) | f (Hz) | Q (m³/h) | H (mm) | Ht (mm) |
|-----|--------|-------|-------|--------|----------|--------|--------|
| 1   | 50     | 45    | 0     | 0      | 12       | 200    | 251    |
| 2   | 50     | 45    | ±5    | 0.1    | 12       | 200    | 250    |
| 3   | 50     | 45    | ±5    | 0.3    | 12       | 200    | 252    |
| 4   | 50     | 45    | ±5    | 0.5    | 12       | 200    | 251    |
| 5   | 50     | 45    | ±5    | 0.67   | 12       | 200    | 251    |
| 6   | 50     | 45    | ±5    | 0.75   | 12       | 200    | 250    |
| 7   | 50     | 45    | ±5    | 0.83   | 12       | 200    | 251    |
| 8   | 50     | 45    | ±5    | 1      | 12       | 200    | 253    |
| 9   | 50     | 45    | ±5    | 1.17   | 12       | 200    | 250    |
| 10  | 50     | 45    | ±5    | 1.33   | 12       | 200    | 250    |

The velocity measurements were performed by an ultrasonic Doppler velocity profiler (UDVP). The UDVP consists of a piezoelectric probe, which works both as emitter and receiver of a ultrasonic bursts signal responding to the flow velocities. The UDVP is able to capture the instantaneous flow velocities parallel to the probe and able to perform a moving average filtering over time. The UDVP have been widely used in the field of flow velocity measurements [10]. For a detailed description of the UDVP technique, see reference [11]. During the present experiments, two probes with the emitting frequency of 1 MHz and a diameter of 10 mm were used to measure the horizontal and the vertical velocity components. The sampling frequency of the UDVP was set as 24 ms/time. Velocities measurements were performed in the vertical 2-D plane along the jet pipe centerline. As shown in Figure 2, UDV probes, A and B, were set in two directions respectively along X-axis and Y-axis. Probe A was moved every 10mm in X-axis direction from the position of x = 100 mm to x = 1000 mm, while probe B was moved every 5mm from the position of y = 5 mm to y = 100 mm. According to the sampling frequency of the UDV probe, statistical average calculations can be used to obtain the instantaneous velocities of the oscillating jet-flow, the undulation pattern on the near bed region, and the cross-sectional profile of the flow velocity at each phase.

3. Results and data analysis
This paper describes instantaneous, temporal and spatial characteristics the oscillating wall jets by the averaged cross-sectional velocity profiles, phase evolution of the turbulent velocity profiles and velocity decay along the plane.
3.1. Velocity profile of the oscillating wall jet

Velocity profiles of the wall jet induced by the impingement jet without oscillation present stable and self-similar during its propagation [12]. The oscillating wall jet inherits some of the characteristics of the former one during its phase evolution and frequency variance, such as the steady boundary layer thickness, \( \delta \). The boundary layer thickness of the oscillating wall jet in a certain downstream location is observed approximately consistent for different oscillating phases and oscillating frequencies. For a certain location of \( x/D=3 \), \( \delta \) is approximately 0.2D. The consistent \( \delta \) of the oscillating wall jet may be due to the adsorption of the wall and the viscosity of the fluid, agreeing with the properties of stagnation flows [8]. It is more stable than the vertical distance \( y_{0.5} \) where the flow velocity is half of the section maximum velocity. The unsteady \( y_{0.5} \) involves the different turbulence when the wall jet mixes with the external flow field at different oscillating phases and frequencies. To study the flow features of the oscillating wall jet in a normalized form, this study normalizes the vertical distance by the boundary layer thickness \( \delta \), rather than \( y_{0.5} \).

The velocity profiles of the oscillating wall jet maintain stable in its phase-evolution. Figure 2 shows the profiles development of the mean flow velocity \( \bar{u} \) in the center plane of the oscillating wall jet for five typical phases from the valley value phase \( \omega t = 0 \) to the peak value phase of \( \omega t = \pi \) in a normalized form against \( y/\delta \). The observed data were detected at the location of \( x/D = 3 \), for Run (3). As can be seen in Figure 2(a), when normalized by the velocity at the jet nozzle \( u_0 \), \( \bar{u}/u_0 \) sharply declines in the region below the boundary layer thickness at each oscillating phase. Close inspection of the section velocity for each phase shows a clear inflection point \( u_{mp} \) at the boundary layer thickness \( \delta \). And \( u_{mp} \) varies periodically in the range of the peak value \( u_{pc} \) and valley value \( u_{vc} \) of the cycle. In the present experiment, \( u_{pc}=0.26u_0 \) and \( u_{vc}=0.72u_0 \). The clear \( u_{mp} \) allows it to be considered as a characteristic flow velocity for discussion. Figure 2(b) shows the averaged flow velocity \( \bar{u} \) normalized by \( u_{pc} \). For the present oscillating frequency of 0.3Hz, data of \( \bar{u}/u_{pc} \) are well clustered in the vertical distances of \( y/\delta = 0-3 \). Only slight deviation for data of \( \omega t = 0 \) and \( \omega t = \pi \) appear at the upper edge of the boundary layer. Taking the vertical distance of \( \bar{u}/u_{pc}=0.5 \) for example, \( y/\delta \) is 3.24 at \( \omega t = \pi \), while \( y/\delta=2.87 \) as at \( \omega t = \pi/2 \). Degrees of deviation from the Weibull distribution [3] of steady wall jet are 12.9% and 0.3%, respectively. It illustrates that the velocity profile of the oscillating wall jet presents relative stable profiles during its phase-evolution, only slight departure happening in the upper edge of the boundary layer.

![Figure 2. Phase-variant velocities of the oscillating wall jet.](image-url)
separation of $u/u_{pc}$ increases with the increment of oscillating frequency. It may be due to that the oscillating wall jet with higher frequency mixes with the ambient fluid more violent, resulting in a range extension of the upper edge of the boundary layer. However, the velocity profile at each oscillating frequency shows good consistency and stability in the inner boundary layer. Data of averaged velocity at each height is tightly clustered around the near-wall logarithmic line. It seems no apparent influence of the velocity profile in the inner boundary layer induced by the oscillating frequency. In general, higher frequencies of the oscillating wall jet expand its upper edge of the boundary layer, but the flow field of the inner boundary layer is affected little by the oscillating frequency.

Figure 3. Velocity profiles of the oscillating wall jet for different frequencies.

3.2. Turbulence induced by the oscillating wall jet

The turbulence fluctuation $u'$ induced by the oscillating wall jet is phase-dependent. Figure 5 shows a statistical vision of the temporal variation of the maximum velocity at $x/D = 3$ for the oscillating frequency of $f = 1.16$ Hz. In Figure 5, the boxplots describe 5 periods of 2500 values for section maximum velocity $u_{mc}$ measured with the sampling frequency of 24 ms$^{-1}$ and sampling time of 60 s. As can be seen, the velocity of the oscillating wall jet is distinctly separated into the current attributed part, $u_c$, and the wave attributed part, $u_w$. Meanwhile, the wave attributed part, $u_w$, seems good agreement with a sinusoidal function (or cosinoidal one for different initial phase) when neglecting the turbulence fluctuation, written as:

$$u = u_c + u_w = u_c + u_wA \sin(\omega t + kT)$$

(1)

where $u_c$ is obtained as the offset of the oscillation at each section, and $u_wA$ stands for the amplitude of the wave. The turbulence fluctuation appears relatively tiny to the main velocity. From the over all trend, the maximum velocity fluctuations during the oscillation period is approximate ±5% of the current phase maximum velocity, having little effect on the tendency of the section maximum velocity over time. A closeup look at the velocity boxes, the lengths at the peaks and valleys are generally longer than at the other phases, illustrating the turbulence fluctuation varies with the oscillating phase. Taking the high-speed suppression phase $\omega t_4$ as an example, the velocity fluctuation value exceeds 3 times than fluctuations at the acceleration phase $\omega t_2$. In addition, the velocity fluctuations near the phase of $\omega t_0$ and $\omega t_4$ also exhibit a dense pattern of large fluctuation, and the velocity fluctuations throughout the oscillation period are mainly concentrated in these two regions. This fact reflects that the oscillating wall jet produces more turbulence during the low-speed provocation and high-speed suppression than that at the accelerating and decelerating phases. A few values deviate greatly from the average velocity of its same phase, which illustrates the random violent turbulence would be produced inevitably during
the oscillation. Fortunately, these deviations are still not very large relative to the averaged instantaneous velocity, and the occurrences are infrequent. On the other hand, the section maximum velocity presents oscillating with the same frequency as that of the jet nozzle swing, appearing negligible phase lead and decay. The acceleration phases and deceleration phases have good symmetry for peak values and valley values. As a result, the temporal change of section maximum velocity $u_{max}$ is good fitted to a sinusoidal curve.

![Figure 4](image)

**Figure 4.** Statistical vision of temporal curve of the oscillating wall-jet velocities ($x=300\text{mm}$, $f=0.833 \text{Hz}$).

The turbulence of near bed region for different oscillating frequencies can be compared when characterized turbulence fluctuations by the maximum velocity fluctuations at high-speed suppression phase of $\omega t_4$ in Figure 4, as shown in Figure 5. The turbulence fluctuation range for steady wall jet ($f=0$) is between $\pm 2.65\%$, while that for oscillating wall jet of $f=1.33\text{Hz}$ is between $\pm 5\%$. And the range of turbulence fluctuation seems to increase with the increment of the oscillation frequency. However, this trend is confined in the overall data, but not significant for the data of 25%-75% statistical velocity fluctuations. The former includes all data with flow stability and randomness, while the latter is a representation of statistical stability. Comparing to the increasing trend of the velocity fluctuation range versus oscillating frequency, 25%-75% statistical velocity fluctuation seems to maintain relative constant against the frequency of the oscillation. A reasonable explanation for the two inconsonant trends is that the increment of the oscillation frequency increases the possibility of mixing between the wall jet and the external flow field, but affects insignificantly on the structural stability inside the boundary layer of the oscillating wall jet.
3.3. Decay of the oscillating wall jet

Figure 6 shows the observed uc/u0 of the oscillating wall jet along x/D from the location of the maximum oscillation offset uc0/u0. As can be seen, decays of uc/u0 along x/D for different frequencies present continuously decreasing in the range of x/D≤8. In terms of uc/u0 at x/D>8, data begins to diverge, and exhibiting undulating decay against x/D.

It should be noted that, the spatial characteristic of the wall jet is normally described by the decay performance along the downstream wall [5, 6]. The wall jet starts from the stagnation point where the flow velocity on the plane is zero [7], thereafter experiences a transition region that the velocity increases from zero to a maximum value at a certain downstream distance x, and then decreases continuously in the wall jet region. Unfortunately, this study did not apparently observe the trajectory of stagnation point for the oscillating wall jet at any frequency. It may be due to the turbulence induced by that the oscillating wall jet leads to an unsteady flow fields around the stagnation point, resulting in difficulty of the observation for the instantaneous stagnation point. However, the point of maximum oscillation offset uc0, together with the maximum oscillation amplitude, uwAm, can be distinguished obviously. At the downstream of the maximum velocity point, both the normalized offset, uc0/u0, and the normalized amplitude, uwAm/u0, decay with the development of the oscillating wall jet on the wall. The maximum
value of $u_{cm}/u_0$ takes place at approximately $x/D=2$ downstream the impingement points of $\theta=45^\circ$, only with a slight spreading in the downstream direction for different oscillating frequencies.

The decay law of the oscillating wall jet is comparable to that of the wall jet induced by the impingement oblique jet. In terms of the later one, the decay law of $u/u_0$ along the plane is supposed related to the impingement angles, written as:

$$u/u_0 = f(\theta) (x/D)^m$$

where $m$ is the exponent, empirical value is $m=-1$ [2, 6]; $f(\theta)$ is the decay coefficient related to the impingement angles, reference [2] gave the function as $f(\theta)=1.1(1+\cos\theta)/\sqrt{\sin\theta}$, while reference [6] gave it as $f(\theta)=396/(\pi\theta)$, which is suitable for the conditions of $(4\leq x/D\leq 12)$ and $45^\circ \leq \theta \leq 90^\circ$. Both functions indicate that the decay coefficient increases with the decrement of $\theta$, the subtle difference may be due to the different vertical distance between the jet exit and plane, $H/D$, as the former experimented in the range of $H/D = 10~34$, while the later at $H/D=3$. The present experiments are performed with a fixed vertical distance of $H/D=4$, whose data are suitable for the comparison with the above decay law of the steady impingement jet. As shown in Figure 6, data of $u_c/u_0$ for low oscillating frequencies ($f \approx 0.1$ Hz$\sim$0.5 Hz) maintain good agreements with the formulae of Beltaos (1977) [2] for $\theta=45^\circ$, and Wang et.al. (2017) [6] for $\theta=60^\circ$. However, this similarity tends weak for higher oscillating frequencies, data of $u_c/u_0$ fall together and lower than data for low oscillating frequencies. The decay rate for each oscillating frequency in the range of $x/D < 7$ is between the calculated values of $45^\circ \sim 60^\circ$ by the formulae of Wang et.al. (2017) [6]. Whereas when $x/D > 7$, larger discrepancies locate away from the decay law of the steady impingement jet, and data of $u_c/u_0$ present unstable to $x/D$. For the oscillating wall jet at higher oscillating frequencies ($f = 0.67$ Hz$\sim$1 Hz), $u_c/u_0$ present steeper slope than the steady wall jet. On the other hand, the decay rates seem increasing with the increment of the oscillating frequencies. It may be due to the higher probability of the oscillating wall jet mixed with the external flow field at higher oscillating frequencies. The more violent fluctuations dissipate more kinetic energy of the wall jet flow, leading to a more rapid velocity decay of the oscillating wall jet.

Figure 7 shows the development of the normalized amplitude of oscillating wall-jet flow $u_{wA}/u_0$ along the plane. The observed data for different oscillating frequencies also present a continuous decay trend in the forward flow direction. However, the dispersion of $u_{wA}/u_0$ is larger than that of $u_c/u_0$, especially after ($x/D > 5$). Suppose $u_{wA}/u_0$ for different oscillating frequencies obey a same decay law, the observed data seem good fitted to an exponent decrement of $u_{wA}/u_0$ against $x/D$ in the range of $2<x/D<15$, written as:

$$u_{wA}/u_0 = 0.176 e^{-0.162(x/D)}$$  \hspace{1cm} (3)

the square of the correlation coefficient is $R^2=0.98$. 

Figure 7. Decay of velocity amplitude for oscillating wall jet.
4. Conclusion

In this study, the oscillating wall jet flow induced by the swinging oblique impingement jets of the initial oblique angle of 45°, the pendulum angles of ±5°, and ten swing frequencies (f = 0-1.33 Hz) are experimentally investigated, the following conclusions are obtained:

1). In the inner boundary layer, velocity profiles of the oscillating wall jet maintain good agreement with the logarithm distribution, unaffected by the oscillating phases and frequencies, and generally follows the Weibull distribution, similar to the steady wall jet. However, in the outer boundary layer at y > δ, the separation of u∕upc range slightly increases with the increment of oscillating frequency, whereas affected slightly by the oscillating phases.

2). Greater fluctuation magnitudes are produced by the oscillating wall jet during the low-speed provocation and high-speed suppression than that at the accelerating and decelerating phases. The overall data of the velocity fluctuations at the boundary layer thickness increase with the increment of the oscillating frequencies. However, the observed data of 25%-75% statistical velocity fluctuations still present the stability of the flow structure of the oscillating wall jet at different frequencies.

3). Both the oscillation offset uc∕u0 and amplitude uwA∕u0 of the oscillating wall jet decay continuously with the spreading distance x∕D. The decay rate of uc∕u0 along the downstream wall of the oscillating wall jet is higher than that induced by the steady wall jet of same angle, and increases with the increasing oscillating frequency. The oscillating amplitude uwA∕u0 decays exponentially with x∕D in the range of 2<x∕D<15.

Acknowledgments

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