Three-dimensional flow observation on the air entrainment into a vertical-wet-pit pump

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Abstract. The authors consider the air entrainment into a suction pipe which is vertically inserted down into a suction sump across a mean free-water surface. This configuration is often referred to as the “vertical wet-pit pump,” and has many practical advantages in construction, maintenance and operation. Most of the flows appearing in various industrial and environmental problems like the present suction-sump flow become often complicated owing to both of their unsteadiness with poor periodicity and their fully-three-dimensionality. In order to understand the complicated flow inside a suction sump in the vertical-wet-pit-pump configuration, the authors experimentally observe the flow using the three-dimensional particle tracking velocimetry (3D-PTV) technique, which includes more unknown factors in accuracy and reliability than other established measuring techniques. So, the authors examine the simultaneous measurement by the 3D-PTV with another velocimetry the ultrasonic velocity profiler. As a result, under the suitable condition with high accuracy, the authors have revealed the complicated flow.

1. Introduction

Our aim is to understand the complicated flow inside a suction sump in the vertical-wet-pit-pump configuration. Most of the flows appearing in various industrial and environmental problems like the present suction-sump flow become often complicated owing to both of their unsteadiness with poor periodicity and their fully-three-dimensionality [1-3]. So, in instantaneous and three-dimensional observations of such flows could give us useful and effective information.

In this context, a three-dimensional particle tracking velocimetry (hereinafter, referred to as 3D-PTV) is one of the potential solutions against such problems. The 3D-PTV is a technology to specify three-dimensional positions of tracer particles from a couple of stereo images, and to obtain the velocity vectors of tracer particles from their positions at different instants. The 3D-PTV has some advantages. Furthermore, if we record the stereo images using video cameras, we can get a temporally-consecutive series of instantaneous and three-dimensional information of the whole flow. So, various 3D-PTV systems have been developed until now [4-11].

Despite the above advantages, the use of the 3D-PTV has been restricted. One of the main reasons exists in the difficulty to estimate its accuracy. So, at the present stage, it is rational to suppose that all the 3D-PTV measurements should be inevitably accompanied by the other verifying measurements using well-established techniques, to assure the 3D-PTV’s accuracy.

In the present study, our concern is the complicated flow inside a suction sump in the vertical-wet-pit-pump configuration. To obtain the information of such unsteady and three-dimensional flow, we
examine the simultaneous measurement using both of the 3D-PTV and another velocimetry, namely, an ultrasonic velocity profiler (hereinafter, referred to as UVP) with common tracer particles, that is, the simultaneous measurement by the 3D-PTV with the UVP. The UVP has proposed and developed by Takeda [12] and Takeda et al. [13]. This simultaneous measurement is expected to become an effective method to dissolve the above fatal defect of the 3D-PTV. In general, the UVP tends not to be applicable for a small number of large tracer particles. On the other hand, the 3D-PTV tends not to be applicable for a huge number of small tracer particles. —The upper and lower limits concerning both the number and the size of tracer particles are important information from a practical point of view. The number in the present 3D-PTV’s measurement volume is in the order of $10^2$ to $10^3$, owing to restricted computational time. The size in the present study is in the order of $10^{-4}$ m to $10^{-3}$ m, while the size in the order of $10^{-5}$ m allows detection with a brighter lighting system and with a narrower measurement volume (see [11]). However, in the present study, we do not attempt to exactly specify the limits for the 3D-PTV, as the present purpose is to conduct the simultaneous measurement.— Under the suitable conditions for the simultaneous measurement, we attempt to reveal the time-mean and instantaneous velocity vectors of the unsteady and three-dimensional flow inside the suction sump.

Of course, we may consider alternatives to the UVP as the verification measurements of the 3D-PTV, such as a hot-wire velocimetry (HWV), a laser-Doppler velocimetry (LDV), a two-dimensional or three-dimensional particle-image velocimetry (PIV) and a two-dimensional particle tracking velocimetry (2D-PTV). However, they are not suitable for the verification measurements of the 3D-PTV in the present study.

2. Model and experimental method

2.1. Model and governing parameters

Figure 1 shows the present model, which is a simple system of a suction sump and a suction pipe with the vertical-wet-pit-pump configuration. Geometric parameters $D$ and $d$ are the outer and inner diameters of the suction pipe, respectively. The former is used as a characteristic length scale. The latter is fixed to $0.9D$. The suction-pipe intake has a bell-mouth shape. —The diameter of the bell mouth is the same as $D$, having a simple geometry with less parameters. We should note that the influence of the bell mouth diameter upon the critical condition for the air entrainment is negligible according to Tagomori [14], as $D < 1.75d$. — The pipe is placed vertically on the centre line of the suction sump. Three geometric parameters $B$, $X$ and $Z$ denote the breath of the suction sump, the clearance from the suction-pipe centre to the suction-sump back wall and the clearance between the suction-pipe intake and the suction-sump bottom wall, respectively. A geometric parameter $H$ is water level, namely, the height of a mean water-free surface, then the pipe’s submergence depth $S$ is equal to $(H – Z)$. A characteristic velocity scale is the mean flow velocity $U_i$ at the suction-pipe intake, which is defined by $4Q/(\pi D^2)$, where $Q$ is inflow rate, or the flow rate into the suction pipe. We define the Froude number $Fr$, the Reynolds number $Re$ and the Weber number $We$ by $U_i/(gD)^{1/2}$, $\rho U_i D/\mu$ and $U_i (\pi D/\mu)^{1/2}$, respectively. Letters $g$, $\mu$, $\rho$ and $T$ denote the gravitational acceleration, fluid viscosity, fluid density and water-to-air surface tension, respectively.

Table 1 summarises chief experimental parameters and their values in the main test of the present study, together with geometric and kinetic parameters in non-dimensional forms. These values are the same as those in one of the two test cases in Funaki et al. [1] where not instantaneous but time-mean flow of the same system of a suction sump and a suction pipe as the present system is revealed by the UVP. Funaki et al. call the test case Case A. —Concerning two kinetic parameters $Re$ and $We$ except for $Fr$, it might be appropriate to suppose the threshold value above which we ignore the influence of a kinetic parameter [3, 15 & 16]. According to our previous study [3] which concludes that the threshold values of $Re$ and $We$ are $3 \times 10^3$ and 12, respectively. Thus, we should account for $Re$ effects, when the present results in Case A are applied to practical aspects with large $Re$’s.—
wall and on the suction-axis is horizontal and convection flow in the the $y$ axis is horizontal mean convection flow, the $x$ axis is horizontal and parallel to the mean suction-summ channel, and normal to the

![Diagram of coordinate system and parameters](image)

**Figure 1.** Model: suction sump and suction pipe in the vertical-wet-pit-pump configuration, together with coordinate system.

| Parameter | Value |
|-----------|-------|
| $D$       | 38 mm |
| $d$       | 34 mm |
| $B/D$     | 3.16  |
| $X/D$     | 1.58  |
| $Z/D$     | 0.39  |
| $S/D$     | 1.19  |
| $U_i$     | 0.6 m/s |
| $U_c$     | 0.095 m/s |
| $Fr$      | 0.98  |
| $Re$      | $2.2 \times 10^4$ |
| $We$      | 14    |

**Table 1.** Experimental parameters.

![Diagram of experimental apparatus](image)

**Figure 2.** Schematic view of a close-up experimental apparatus near a suction pipe for simultaneous measurement using both of 3D-PTV and UVP.
the $z$ axis is vertical. We define three velocity components in the $x$, $y$ and $z$ directions as $v_x$, $v_y$ and $v_z$, respectively.

2.2. Experimental apparatus

In the main test of the present study, an experimental apparatus is substantially identical with our previous studies [1-3]. A turbopump feeds working fluid (water) to a suction sump from a reservoir. We control the flow rate of the pump by a control valve, and then control the water level $H$ in the suction sump. In the upstream of the suction sump, we put a strainer to make flow uniform. A bend-type jet pump sends water up from the suction sump into the suction pipe, because the jet pump tends to induce less swirling than ordinary pumps. The jet pump itself is driven by another turbopump. Water from the suction pipe falls into the reservoir, then a water-circulation system is closed.

Figure 2 shows a schematic view of a close-up experimental apparatus near the suction pipe to explain the simultaneous measurement using both of the 3D-PTV and the UVP. A 3D-PTV system consists of the following: a YAG laser (No. 5 in the figure) with its power supply (No. 6) as a light source, a couple of high-speed video cameras (No. 4) with a frame rate of 1/500 s, and a personal computer (No. 3) on which we conduct 3D-PTV analyses. The 3D-PTV requires more than two cameras which are synchronised with each other to take plural photographs at the same instant. We use a couple of cameras. As shown in Fig. 2, one camera is located outside the back wall of the suction sump, and the other camera is located outside the side wall of the suction sump. A UVP system consists of the following: an ultrasonic transducer (No. 7) as a UVP probe which is placed outside the suction sump, and a UVP monitor (No. 8) for the simultaneous measurement with the 3D-PTV.

The details of the 3D-PTV measurement is as follows (also, see [10, 11]). The 3D-PTV system is calibrated in advance, then we take a couple of stereo images of a measurement volume using two high-speed video cameras with a frame rate of 1/500 s as shown in Fig. 2. Total recording time is 0.6 s, which represents 300 frames. This total recording time might not be enough for the flow (see Subsection 4.3), because of the restriction of the 3D-PTV system like the equipped memory size. Each image adequately covers the measurement volume. Next, we calculate the three-dimensional positions of tracer particles from couple of stereo images. The velocity vectors of tracer particles are determined from two consecutive information of the tracer-particle positions. All data processings have been done in a personal computer. Details is as follows.

For the 3D-PTV calibration, first, we fix two cameras so that their fields of view just cover up the whole measurement volume. If possible, two camera centers should cross, and should be right-angled with each other, to attain higher accuracy. Second, we set as many datum points as possible in the measurement volume, and take a couple of stereo photographs. The three-dimensional positions of these datum points are known in advance. In the present study, the number of the datum points is 43. Thirdly, we can determine a coordinate system, by which we construct a virtual space corresponding to the real space in the personal computer.

For the specification of the tracer-particle positions in three dimensions, we use four consecutive series of informations. First, we specify the centre positions of tracer-particles on each two-dimensional photograph, through a digital image processing. Namely, after the removal of the background image which is the ensemble mean of stationary pixels during all the measuring time, we consider the maximum luminosity position as the tracer-particle centre. In order to identify each tracer particle from surrounding tracer particles, we suppose two thresholds, that is, the minimum size of the tracer particle and the minimum luminosity for the tracer particle. These thresholds can make the identification more accurate, but we should specify appropriate values depending on experimental conditions. Second, we determine the straight line on which there exist both a tracer-particle centre and a camera’s view point. Then, we can see that a tracer-particle position is decided on the coordinate system as an intersection of the two straight lines from a couple of stereo images. Now, we know all the tracer-particle positions in the real 3D space on each time step. For the identification of the same tracer particle on different time steps, a genetic algorithm is used, based on successive four time steps’
data. So, we can get tracer-particle velocity vectors which are obtained from successive two time steps’ data.

The details of the UVP measurement is as follows (also, see [1]). Using the UVP, we can get fine-time-resolution informations, which are not merely the time histories of velocity vectors on a few spatially-fixed points like HWV and LDV. That is, we can get instantaneous velocity profiles by the UVP in terms of the Doppler effect of ultrasonic echoes. The UVP has an advantage on accuracy in comparison with the PTV and the PIV, and does not require clearly-visualised photographs. In the present study, we use a UVP of UVP X-2-PS by Met Flow SA with a frequency of 4 MHz. The number of measuring points is 128 in one profile, and then, the space resolution on the profile is 0.75 mm. As the diameter of the ultrasonic beam is 5 mm, one measuring volume is a disc with a diameter of 5 mm and with a thickness of 0.75 mm. We get consecutive 1024 profiles in each measurement with an interval of 32 ms or more.

We should note that the UVP enables us to know only one component of velocity vectors, which is parallel to the axis of the UVP probe an ultrasonic transducer. Moreover, the spatial range for the measurement is restricted. As the position of the UVP probe is outside the suction sump in order to avoid disturbing flow, it is difficult to conduct the measurements far upstream.

To make sure the effectivity of the present measurement further, we conduct another measurement using a still camera with a shutter speed of 1/20 s as a conventional technique with high reliability and low accuracy, in addition to the simultaneous measurement with the UVP. —By the still-camera-measurement technique, we visualise path lines (paths), namely, time integrals with low accuracy and high reliability. Smaller data-process number of this technique than other technique brings us high reliability in addition to the robustness due to the time integrals.—

3. Results and discussion

3.1. Time-mean flow

Figure 3 shows an example of the simultaneous measurement using both of the 3D-PTV and the UVP on the complicated flow in the actual suction sump in the main test, together with the measurement using a still camera as a conventional technique with high reliability and low accuracy. More specifically, the figure shows the profile of the x-component of time-mean flow-velocity vector averaging over 0.6 s at $y/D = 0.79$ and $z/D = 1.05$. To be exact, the averaging time in the still-camera measurement corresponds to 1/20 s, which is much shorter than the 3D-PTV and the UVP. To conclude, we can see good agreement from a qualitative viewpoint among the 3D-PTV, the UVP and the still-camera measurement despite the complexity of the flow. From a quantitative viewpoint, we can confirm that an average of the relative error to the maximum $v_x$ of the 3D-PTV from the UVP is 13 %, although the relative error locally attains 24 % at $x/D \approx -0.5$.

Figure 3. Time-mean velocity profile at $y/D = 0.79$ and $z/D = 1.05$. 
Concerning the averaging number and the averaging time to obtain the time-mean velocity vectors, Funaki et al. [1] has shown in the UVP measurement on the same flow as the present study that a 200-averaged result is in good agreement with a 500-averaged one, while a 50-averaged one begins to differ from a 500-averaged one especially in the downstream of the suction pipe (at $x/D > 0$). So, Funaki et al. have concluded that the averaging number of 200 is enough. The averaging time corresponding to this averaging number of 200 is equal to 6.4 s. In the present study, we conduct each 3D-PTV measurement with an averaging number of 300 and an averaging time of 0.6 s, and each UVP measurement with an averaging number of about 10 and an averaging time of 0.6 s corresponding to a measuring interval of 65 ms. In the still-camera measurement, the corresponding averaging number and time are 1 and 1/20 s, respectively. Although the averaging time of the 3D-PTV will be further examined at least, this seems not fatal to discuss the present flow from a qualitative point of view, because the present flow is almost steady without large perturbations (as will be mentioned below) especially in the upstream of the suction pipe (at $x/D \geq 0$) where perturbations are much smaller (as will be shown in Figs. 4 and 11). The still-camera measurement is conducted inconsiderably in the upstream of the suction pipe.

Now, we have acquired the reliability and the accuracy in measurements by the 3D-PTV in the present suction sump. So, we will reveal the flow next by the 3D-PTV measurement. Figure 4 shows the time-mean flow obtained by the 3D-PTV. Specifically speaking, the figure denotes the projections on the $y$-$z$ plane of the time-mean velocity vectors in six cross sections. Figures (a), (b), (c), (d), (e) and (f) are at $x/D = -1.32, -0.79, -0.26, 0.26, 0.79$ and 1.32, respectively.

The present flow is the same as that in one of the two test cases in Funaki et al., which is called Case A. In Case A, we commonly observe the air entrainment from the free surface into the suction pipe. More specifically, there stably exist a pair of symmetric air strings (or string-like air bulks) from the free surface to the suction-pipe intake into the suction sump, whose positions are in the downstream of the suction pipe. Owing to small perturbations, the symmetry is occasionally broken. At such an instant, one or none air string appears instead of the symmetric twin air strings.

![Figure 4. Time-mean velocity vectors by 3D-PTV.](image)
Funaki et al. have summarised their results based on the UVP measurement in a schematic diagram (see figure 5), which represent the time-mean and three-dimensional flow structure near the suction pipe in the same flow as the present study. That is, the flow is symmetric about the vertical centre plane of the suction sump. In the downstream of the suction pipe, there exist two vortex filaments A-3 and A-4 with large-magnitude vorticities. One end of each vortex filament reaches the free surface, and the other end reaches the suction-pipe intake. These vortex filaments usually accompany the air strings, which correspond to the air cores by the air entrainment into the suction-pipe intake. In the upstream of the suction pipe, there exist a pair of vortex filaments A-1 and A-2 with opposite rotations, whose axes are longitudinal.

In Fig. 4, the flows in the upstream and in the vicinity of the suction pipe at $x/D \leq 0.26$ (in figures (a) – (d)) resemble one another. In other words, the fluid at $y/D > 0$ tends to concentrate toward the centre on the suction-sump bottom from the centre near the free surface with a clockwise turning motion. On the other hand, the fluid at $y/D < 0$ tends to concentrate toward the centre on the bottom from the centre near the free surface as well, but with an anticlockwise turning motion. Then, we can recognise the symmetric flow about the vertical centre line at $y/D = 0$, in each figure. These two symmetric turning motions are consistent with the vortex filaments A-1 and A-2 which are suggested on the basis of the UVP measurement by Funaki et al. Besides, we clearly see that a remarkable converging point of flow appears near the centre of the suction-sump bottom in each figure. On the other hand, we clearly see no diverging points, because of the existence of the suction pipe in figures (c) and (d), and because of very-small values of the magnitude $(v_x^2 + v_z^2)^{1/2}$ of the projected velocity vector in figures (a) and (b) where we see ambiguous diverging/saddle points in an area at $y/D \approx 0$ and $z/D \approx 1$ instead of one clear diverging point. Of course, the very small magnitude in the area is consistent, because the mainstream component $v_x$ in the $x$ direction is much more dominant than the others almost everywhere. Then, it tends to induce the symmetry’s breaking in the area.

Again in Fig. 4, the flows in the downstream of the suction pipe at $x/D > 0.26$ (in figures (d) and (e)) resemble each other, as well. In other words, we cannot see one clear converging point in contrast with figures (a) – (d). The fluid at $y/D > 0$ is almost in a clockwise circulating motion with a centre at $y/D \approx 0.5$ and $z/D \approx 1$. On the other hand, the fluid at $y/D < 0$ is almost in an anticlockwise circulating motion with a centre at $y/D \approx -0.5$ and $z/D \approx 1$. Then, we can recognise the symmetry of flow about the vertical centre line at $y/D = 0$, in each figure. These twin symmetric circulating motions are consistent with the vortex filaments A-3 and A-4 by Funaki et al., as well. Besides, we clearly see an upward streaming at $y/D \approx 0$, in contrast with figures (a) and (b) where we see a rather downward streaming due to the existences of the remarkable converging point near the bottom and the ambiguous diverging/saddle-points area near the centre.

![Figure 5. Time-mean flow structure by UVP (Funaki et al., 2008).](image-url)
Figure 6 shows time-mean velocity vectors by the UVP on the y-z plane at x/D = 0.63 (Funaki et al.). Figure 7 shows the paths of tracer particles by a still camera on the y-z plane at x/D = 0, with a shutter speed of 1/20 s. —Of course, the tracer-particle condition is much different from Condition II. — As these figures well correspond to Fig. 8 in spite of much different averaging times from figs. 6 and 7, we can again confirm the reliability and the accuracy of the present 3D-PTV measurement.

As well, we compare the time-mean flow in the x-z plane, instead of the y-z plane. Figures 8, 9 and 10 show time-mean velocity vectors by the 3D-PTV at y/D = –0.66, time-mean velocity vectors by the UVP at y/D = –0.63 (Funaki et al. [8]), and the paths of tracer particles by a still camera at y/D = 0.79. We can see that the flows in these figures resemble with one another, that is, there exist (1) a downward streaming at x/D ≈ 0.5 and (2) a clockwise circulating motion with a centre at x/D ≈ 0.5. Then, we can confirm the reliability and the accuracy of the present 3D-PTV measurement, three times.

3.2. Instantaneous flow

From such an observation as the air strings in the present flow are stable, we can anticipate that the present flow is stable as well. In fact, the instantaneous flows obtained by the 3D-PTV at most of measuring instants are similar with the time-mean one shown in Fig. 4. On the other hand, we occasionally observe that the symmetry of a pair of the air strings is broken with poor periodicity. At such instants, the instantaneous flow might be different from the time-mean one. Figure 11 is an example at the instants, where only one air string appears at x/D ≈ 0.8 and y/D ≈ 1.2. —Fortunately, there rarely exist air bubbles which make 3D-PTV’s accuracy worse.— Specifically speaking, the figure shows the projections on the y-z plane of the instantaneous velocity vectors in six cross sections at x/D = –1.32 (in figure (a)), –0.79 (in figure (b)), –0.26 (in figure (c)), 0.26 (in figure (d)), 0.79 (in figure (e)) and 1.32 (in figure (f)), corresponding to the time-mean velocity vectors in Fig. 12.
In Figure 11, the flows in the upstream and in the vicinity of the suction pipe at $x/D \leq 0.26$ (in figures (a) – (d)) resemble one another. Besides, the flow is almost the same as Fig. 4. In other words, we can see (1) the two symmetric turning motions being consistent with the vortex filaments A-1 and A-2, (2) one remarkable converging point of flow near the centre on the suction-sump bottom, and (3) ambiguous diverging/saddle points with very-small magnitudes in an area at $y/D \approx 0$ and $z/D \approx 0$. On the other hand, the flows in the downstream of the suction pipe at $x/D > 0.26$ (in figures (d) and (e)) do not resemble each other, except for a common downward streaming from the free surface at $y/D \approx 1$. The common downward streaming could be affected by the air string which occasionally appears at the instant at $x/D \approx 0.8$ and $y/D \approx 1.2$. Besides, either of both the figures does not resemble Figs. 4(e) and 4(f). Specifically speaking, in Fig. 11(e), we cannot see neither (1) the symmetric twin circulating motion nor (2) the upward streaming near the suction-sump centre (at $y/D \approx 0$). In contrast, in Fig. 11(f), the flow resembles neither one in Fig. 11(d) nor the others in Figs. 4 and 11. In other words, the flow is governed by a single circulating motion with a centre at $y/D \approx 0$ and $z/D \approx 1$. In summary, the instantaneous flow in the downstream of the suction pipe tends to fluctuate much more with complicated flow structures than the flow in the upstream and in the vicinity of the suction pipe which is similar with the time-mean flow at any time.

4. Conclusion
In order to understand the complicated flow inside a suction sump in the vertical-wet-pit-pump configuration, we have conducted the measurement by three-dimensional particle tracking velocimetry (3D-PTV) technique. As the technique includes more unknown factors in reliability and accuracy than other established measuring techniques, we have introduced the simultaneous measurement by the 3D-PTV with another velocimetry. Then, we have revealed the time-mean and instantaneous velocity vectors of the unsteady and three-dimensional flow using the 3D-PTV verified by the UVP in addition to the conventional still-camera measurement. Concerning the time-mean flow, we have confirmed the
reliability and the accuracy of the present 3D-PTV, whose results are consistent with the summary by Funaki et al. (2008) such as four vortex filaments and so on. The instantaneous flow in the downstream of the suction pipe tends to fluctuate much more with complicated flow structures than the flow in the upstream and in the vicinity of the suction pipe which is similar with the time-mean flow at any time. The instantaneous flow in the downstream is closely related with the free-surface behaviour which characterised by symmetry breaking of a pair of the air strings, namely, string-like air bulks in the suction sump.

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