Experimental Study on Occurrence-Time Ratio Measurements of Air Entrainment in a Suction Sump

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Abstract. In order to get accurate measurements of air entrainment in a suction sump, we design some new simple bubble sensors, which can detect the existence of air bubbles inside a suction pipe with no disturbances by the sensors and with a fine spatial resolution. We force on an intermittency factor \( \gamma \), that is, an occurrence-time ratio of the air entrainment, and compare the result by the present sensor with those by conventional two methods; namely, visual and auditory ones. As a result, we show the criteria which specify lower-accuracy conditions in the conventional methods. By the visual method, the accuracy of \( \gamma \) becomes low, when \( \gamma \) is less than 0.05. By the auditory method, the accuracy of \( \gamma \) becomes low, when the submergence depth \( S \) of the suction pipe is close to the critical one \( S_c \).

1. INTRODUCTION

In power generation plants, irrigations, drainages and so on, we have increasingly required the innovations in suction-sump designs for low cost, compact size and high efficiency. In such situations, air entrainments into suction pipes become to appear more frequently. The air entrainments often induce vibration, noise and low efficiency, and sometimes result in pumps’ collapses at the worst.

In the present study, our purpose is to get accurate measurements of the air entrainment into a suction pipe inserted vertically down in a suction sump, which is called as the “vertical wet-pit pump” configuration. Concerning the air entrainment in such a suction sump, there have been several studies (see Iversen, 1953; JSME standard, 1984; Hirata et al., 2003). Recently, in order to reveal the air-entrainment mechanism, the authors have conducted flow-velocity measurements by a UDM (Ultrasonic Doppler Method) and shown three-dimensional time-mean velocity distributions and equi-vorticity contours (Funaki et al., 2007).

Until now, we have usually judged the air-entrainment occurrence by means of a visually-based method (hereinafter, referred to as a visual method). This conventional method has been used prevalingly, because of its practicability and simplicity. However, as this visual method inherently means just the observation of free surfaces (will be described later), we do not identify the air entrainment itself. Then, we should require an accurate assessment on the visual method.

So, we design a new and simple conductance-type electric bubble sensor, which can detect the existence of air bubbles inside a suction pipe with no disturbances by sensor probes and with a fine spatial resolution. We focus upon an occurrence-time ratio of the air entrainment, and compare the result by the bubble sensor with those by conventional two methods; namely, the visual and auditory ones. The auditory method is an auditorily-based method where we use a sound-level meter as a sensor. Because of its simplicity and handiness, the auditory method has been prevalent as well as the visual method, despite the lack of direct relations with the air entrainment.
2. EXPERIMENTAL METHOD

2.1 Experimental apparatus

Figure 1 shows the present model, that is, a simple system with a suction sump and a suction pipe, having a configuration of the vertical wet-pit pump. Here, $D$ is an outside diameter, $B$ a breadth of the suction sump, $X$ a back clearance which is the distance from a suction-pipe centre to a back wall, $Z$ a bottom clearance, and $H$ a height level.

In order to specify a dynamical state, we define the three kinematic non-dimensional governing parameters; that is, the Froude number $Fr$, the Reynolds number $Re$ and the Weber number $We$, as follows.

$$
Fr = \frac{V_b}{(gD)^{0.5}} .
$$

$$
Re = \frac{V_b D}{\nu} .
$$

$$
We = \frac{V_b (\rho D/\sigma)^{0.5}}{\nu}.
$$

$g$, $\nu$, $\rho$ and $\sigma$ denote the gravitational acceleration, kinetic viscosity, fluid density and water-to-air surface tension, respectively. The mean flow velocity $V_b$ at the suction-pipe intake is defined as

$$
V_b = 4 \frac{Q}{\pi D^2},
$$

where $Q$ is the flow rate into the suction pipe. As a supplementary parameter, we use the Bond number such as

$$
Bo = \frac{\rho g D^2}{\sigma}.
$$

When we define governing parameters, we can consider various options in the choice of characteristic scales. In the present study, we choose $D$ and $V_b$ as length and velocity scales, respectively. In Table 1, we summarise the present values of experimental parameters.

Figure 2 shows a schematic diagram of the present experimental apparatus, which is similar with those in references (Hirata et al., 2003; Funaki et al., 2007). A turbo pump B (No. 2 in the figure) feeds working fluid (water) to a suction sump (No. 9) from a reservoir tank. We control the flow rate from the pump A by a valve, and then control the water level in the suction sump. In the upstream of the suction sump, we put a strainer (No. 10) in order to get uniform flow. A bend-type jet pumps (No. 7) pumps up water in the suction sump into a suction pipe (No. 8). Here, the jet pump has less swirling component, than ordinary pumps. The water from the suction pipe and the jet pump falls into a container tank on a platform scale (No. 11).

![Diagram of experimental apparatus](image)

**Fig.1** Suction sump and suction pipe, with a configuration of the vertical wet-pit pump.
Table 1  Experimental parameters.

| Parameter | Value |
|-----------|-------|
| $D$ [mm]  | 38    |
| $d$ [mm]  | 34    |
| $B/D$     | 3.15  |
| $X/D$     | 1.71-2.32 |
| $Z/D$     | 0.71  |
| $S/D$     | 0.8-2.25 |
| $V_b$ [m/s] | 1    |
| $Fr$      | 1.6   |
| $Re$      | $3.8 \times 10^4$ |
| $Bo$      | 200   |
| $We$      | 28    |

In the visual method, we observe free surfaces near the suction pipe, using a camcorder with a frame rate of 60 frames/sec, which is fixed downstream outside the suction sump. In the auditory method, a sound-level meter is placed near the outer wall of the suction pipe and at 0.2m above the suction-pipe intake. We have to determine an adequate threshold value for the sound-level meter, as well as the bubble sensor. The present threshold value is $1.16V_0$ in the output voltage $V$ from the sound-level meter, where $V_0$ denotes the output voltage when the spatially-continuous air core (see later for its definition) does not appear. The threshold values depend upon the sensor location and so on. We will discuss the threshold values of the sound-level meter and the bubble sensor, in the following subsections.

![Experimental apparatus.](image)
2.2 Air-entrainment-occurrence judgment by the visual measurement

The visual method is the most common method to judge the air-entrainment occurrence. However, due to ambiguous definitions of the air-entrainment occurrence, there has existed the confusion among researchers. (The main reason for the confusion, of course, comes from the lack of direct relations with the air entrainment itself.) In the present study, the judgment of the air-entrainment occurrence by the visual method are given by the following manner, which is the same as the conventional manner as in reference (Hirata et al., 2003). When we observe any spatially-continuous air cores from a free surface to a suction-pipe intake, namely, any underwater air bulks accompanied with so-called “the fully-developed entraining vortices even at a short instant,” we recognise the air-entrainment occurrence (see Fig. 3(a)). On the other hand, when we observe some spatially-intermittent air cores, namely, some underwater air bulks accompanied with so-called “the intermittently-developed entraining vortices,” we do not recognise the air-entrainment occurrence (see Fig. 3 (b)).

2.3 Definition of critical submergence $S_c$

We often use a critical submergence $S_c$ as a prime indicator for the air entrainment. The definition of $S_c$ is as follows. When the submergence depth $S$ (see Fig.1) decreases from a sufficiently large value to zero, we can first observe the spatially-continuous air cores at $S = S_c$. In the present experiments, we gradually decrease $S$, with a step of 0.005m. At each step, we search for the spatially-continuous air cores during 300sec. In most cases, duration times of the air entrainment are much shorter than 300sec. Of course, the appearance of the spatially-continuous air cores does not mean the air-entrainment occurrence, exactly.

Incidentally, such a judgment manner is more objective and keeps a good reproducibility which has been confirmed by many preparatory experiments, although it lacks a thoroughly-theoretical background. (In fact, we have also confirmed that the results obtained with much longer sampling times than 300sec almost coincide with the present results.) The present judgment manner is the same as reference (Hirata et al., 2003). Even if we use a somewhat-deferent judgment manner from the present one, the obtained results are considered to be qualitatively the same as the present results (also see Hirata et al., 2003).

![Fig.3](image)

(a) Spatially-continuous air core from free surface to a suction-pipe intake
(b) Spatially-intermittent air core from free surface to a suction-pipe intake

Fig.3 Types of air cores, for the judgment of air-entrainment occurrence.
2.4 Bubble sensor

For an accurate detection of the air entrainment into the suction pipe, we develop a bubble sensor. The bubble sensor utilises the same principle as the conductance-type void-ratio meters (for example, see Hewitt, 1978); namely, it measures the electrical resistance which increases with increasing air volume inside the suction pipe. So, we can instantaneously know the occurrence of the air entrainment by means of monitoring the output voltage.

Figure 4 shows a schematic diagram of the bubble sensor. Two copper ring-shaped electrodes are flush-mounted inside a suction pipe, at 0.2m downstream from the suction-pipe intake. The gap between the two electrodes is fixed to 0.002m, and we impress a constant voltage between them. If air bubbles exist between them, the conductance value changes. Then, we measure the voltage impressed to another resistance in a bubble-sensor series circuit as a real-time output corresponding to this conductance change.

2.2.2 Definition of intermittency factor

We usually record the output voltage from the bubble sensor for 300sec. Using this raw time-series data, we get an intermittency factor \( \gamma \). \( \gamma \) represents the occurrence-time ratio of the air-entrainment to the total recording time. Its definition is given by

\[
\gamma = \frac{\sum_{i=1}^{n} \tau_i}{t_0}.
\]  

(6)

As shown in Fig. 5, during a duration time \( \tau_i \), the \( i \)-th air entrainment occurs. Here, \( t_0 \) denotes the total recording time which is equal to 300sec. And, \( n \) denotes the total number of the air-entrainment occurrence for \( t = 0 - t_0 \). Supplementally speaking, one main reason why we consider \( \gamma \) is that the concerning phenomenon has a very-weak periodicity, and that \( \gamma \) tends to could have a constant value with enough long \( t_0 \).
3. RESULTS AND DISCUSSION

3.1 Comparison on raw time-series data

Figures 6-8 show the raw time-series data of the simultaneous measurements by the three methods; namely, the bubble-sensor method, the auditory method and the visual method. In each figure, the abscissa denotes time. The ordinate denotes the output voltage from the bubble sensor in figure (a), the sound-level meter in figure (b), or the appearance/disappearance of the spatially-continuous air core in figure (c). Figures 6, 7 and 8 are the results at $S/D = 0.80$, $1.65$ and $2.25$ ($\approx S_c/D$), respectively.

Although figures (a), (b) and (c) are simultaneously-measured data, the data are not perfectly synchronised with one another. For example, because the bubble sensor is located somewhat downstream from the suction-pipe intake, such a time lag as about $0.2$ sec occurs in comparison with the air entrainment at the suction-pipe intake. However, time scales of the abscissa of Figs. 6-8 are much longer than the time lag. Then, we have no corrections on the data, because the smaller time lag does not bring us any miss-understandings. Furthermore, the time lag intrinsically does not appear, when we consider the intermittency factor $\gamma$.

The threshold values for the bubble sensor and the sound-level meter should be determined in advance. To begin from the conclusion, we cannot find out the perfectly-accordable values among the three methods, for all the cases tested. However, but for such exceptional cases as the air entrainment occurs rarely (for example, see Fig. 8), we can find out the accordable threshold values among the three methods. In fact, both in Figs. 6 and 7, we can find out the well-accordable threshold values for the bubble sensor and the sound-level meter. In such situations, $S/D$ is smaller than $S_c/D$. So, because the air entrainment occurs frequently, the occurrence-time ratios of the spatially-continuous and spatially-intermittent air cores without the actual air entrainment are considered to become relatively small. Furthermore, the sound-pressure perturbations induced by the air entrainment are also considered to become large.

Now, we temporarily focus our attention upon a single bubble on a suction pipe, in order to consider the threshold value of the bubble sensor. (Of course, it is difficult to suppose a single bubble as an approximation for the actual air entrainment.) Incidentally, because the threshold value of the sound-level meter strongly depends upon its location and its surrounding sound environments we can hardly reveal its physical relations. On the other hand, it is easier to consider the physical relations concerning.

Fig. 5 Intermittency factor $\gamma$. 

\[ \begin{array}{c}
\text{Appearance} \\
\text{Disappearance}
\end{array} \]

\[ \begin{array}{c}
\text{Start} \quad \tau_1 \quad \tau_2 \quad \text{End}
\end{array} \]

$t$ 

$t_0$
Fig. 6  Time histories \((X/D=1.71, S/D=0.80)\).

Fig. 7  Time histories \((X/D=1.71, S/D=1.65)\).
Figure 9 shows the relation between the threshold value $V$ of the bubble sensor and the diameter $\phi$ of a single air bubble between the two electrodes. When we choose 1.9V as the threshold value, we regard the passage of a single air bubble with a diameter $\phi > 0.15D$ (= 5.7mm) as the air entrainment. (Strictly speaking, we also regard the passage of a group of air bubbles with $\phi < 0.15D$ as the air entrainment.) Incidentally, as $\phi$ increases, the error on $V$ tends to increase. This is considered to be related with the air-bubble deformation and the air-bubble eccentricity from the suction-pipe centre with a timely-random fluctuation.

Figure 8 shows different features from Figs. 6 and 7. At first, we compare the bubble-sensor method in figure (a) with the visual method in figure (c). At $t \approx 10$sec, the air entrainment is not detected by the bubble-sensor method, but detected by the visual method. In addition, at $t \approx 90$sec, the duration time of the air entrainment measured by the bubble-sensor method is much smaller than that by the visual method. The above two discrepancies can be explained by frequent appearances of the spatially-continuous air core without the actual air entrainment.

Second, we compare the bubble-sensor method in figure (a) with the auditory method in figure (b). At $t \approx 90$sec, the air entrainment is detected by the bubble-sensor method, but not by the auditory method. This can be explained by the small sound-level component of the air entrainment at $S/D \approx S_c/D$, where the amount of entrained air and the corresponding sound level become small. Then, the relatively-small sound related with the air entrainment tends to be drowned out by the back-ground sound noises due to a pumps operation, water flow and so on.

### 3.2 Intermittency factor of air entrainment

In Fig. 10, we summarise Figs. 6-8. The ordinate and the abscissa denote the intermittency factor $\gamma$ and the reduced submergence depth $S/D$, respectively. For all the three methods, as $S/D$ increases, $\gamma$ decreases monotonously and linearly. In addition, all the values of $S/D$ at $\gamma = 0$, which are obtained by extrapolations, almost coincide with $S_c/D$, which is determined by the visual method. However, the values of $\gamma$ obtained by the three methods at $S/D \approx S_c/D$ do not always coincide with one another.
Fig. 9  Threshold value and bubble diameter $\phi$.

Fig. 10  Intermittecy factor $\gamma$ versus $S/D (X/D=1.71)$.

Fig. 11  Reduced intermittency factor $(X/D=1.71)$. 
Table 2  Summary of comparison among bubble sensor, auditory and visual.

| Method   | Condition                                      |
|----------|------------------------------------------------|
| Auditory | Not accurate at \( S/D = Sc/D \)               |
| Visual   | Not accurate at \( \gamma < 0.05 \)          |

In Fig. 11, we re-plot Fig. 10 in order to see the differences of the auditory and visual methods from the bubble-sensor method. Specifically speaking, the ordinate denote the reduce intermittency factor \( \gamma / \gamma_{\text{sensor}} \) instead of \( \gamma \), where \( \gamma \) is normalized by the intermittency factor \( \gamma_{\text{sensor}} \) by the bubble-sensor method.

In Fig. 11, most of \( \gamma / \gamma_{\text{sensor}} \) are approximately unity except for those at \( S/D = S_c/D \). However, at \( S/D \approx S_c/D \), \( \gamma \) by the visual method is much larger, and \( \gamma \) by the auditory method is slightly smaller than \( \gamma_{\text{sensor}} \). These results well correspond to Fig. 6-8.

Concerning the other many results with different values of \( X/D \), we have finally obtained such a criteria as Table 2. The criteria specifies lower-accuracy conditions in the conventional auditory and visual methods. Specifically speaking, by the auditory method, the accuracy of \( \gamma \) becomes low, when submergence depth \( S \) of the suction pipe is close to the critical one \( S_c \). On the other hand, by the visual method, the accuracy of \( \gamma \) becomes low, when \( \gamma \) is such a small value as less than 0.05.

Incidentally, the value of \( S_c/D \) determined by the visual method is considered to be accurate, when we refer to the results by the bubble-sensor method.

At \( S/D \approx S_c/D \), we cannot anticipate accurate measurements of \( \gamma \) by both the auditory and visual methods, because \( \gamma \) tends to have a small value. At \( S/D \ll S_c/D \), we can anticipate accurate measurements of \( \gamma \) by the auditory method, but cannot always anticipate accurate ones by the visual method.

4. SUMMARY

Until now, we have conventionally judged the air-entrainment occurrence in suction sumps by means of the visual method or the auditory method. These conventional methods have been used prevailingly, because of their practicability and simplicity. However, as the methods inherently mean just the observation of free surfaces or noise level, we do not identify the air entrainment itself. Then, we have required accurate assessments on the methods.

In order to get accurate measurements of air entrainment in a suction sump, we have designed a new and simple conductance-type electric bubble sensor. And, we have focused on the intermittency factor \( \gamma \) (namely, the occurrence-time ratio of the air entrainment), and have compared the result by the bubble sensor with those by the conventional two methods; namely, the visual and auditory ones. As a result, we have shown the criteria which specify lower-accuracy conditions in the conventional methods.

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NOMENCLATURE

\[ B \quad \text{Sump breadth} \quad [\text{mm}] \]

\[ Bo \quad \text{Bond number} \]

\[ D \quad \text{Outside diameter of a suction pipe} \quad [\text{mm}] \]
\( d \) Inside diameter of a suction pipe \([\text{mm}]\)

\( Fr \) Froude number

\( H \) Height level \([\text{mm}]\)

\( Re \) Reynolds number

\( S \) Submergence depth \([\text{mm}]\)

\( t \) time \([\text{s}]\)

\( V_b \) Mean flow velocity \([\text{m/s}]\)

\( We \) Weber number

\( X \) Back clearance \([\text{mm}]\)

\( Z \) Bottom clearance \([\text{mm}]\)

**Greek Letters**

\( \gamma \) Intermittency factor

\( \tau \) Air entrainment occurs

**Subscripts**

\( c \) critical

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