Effect of boundary conditions on the performance of a dropshaft with an internal divider
Jiafang Wei, Yiyi Ma, David Z. Zhu and Jian Zhang

ABSTRACT
Dropshafts with an internal divider for air circulation are proposed to reduce air entrainment in plunging type dropshafts. Dropshafts typically operate under a pressurized downstream condition and with limited air supply from the top. In this study, experiments were conducted to investigate the performance of the dropshaft with an internal divider under different downstream conditions and air inlet conditions. From the experiments, a pressurized downstream condition would increase the air pressure in the dropshaft, reduce the outside air entrainment while increase the internal air circulation. Reducing the size of the air inlet would decrease the air pressure, meanwhile cause an increase in internal air circulation and a reduction in outside air entrainment. A dimensionless parameter of ‘effectiveness factor’ was also proposed to measure the effectiveness of the internal air circulation on reducing the outside air entrainment. This study considers the performance of the dropshaft with a divider under the conditions close to real situations, which is important to its design and application.

INTRODUCTION
Dropshafts are the vertical drop structures used in urban drainage systems to transfer water from shallow sewers to deep tunnels. Plunging type dropshafts are the most commonly used dropshafts. However, plunging dropshafts can entrain a large amount of air and pressurize the air space of downstream sewers. The subsequent release of the air has been considered one of the main causes of sewer odor issues (Edwini-Bonsu & Steffler 2006). Camino et al. (2015) reported the air entrainment of the dropshaft of various drop heights and found that a larger drop height resulted in a higher air demand. The relative air demand (the ratio of entrained air flow rate to the water flow rate) was reported to be about 1.4 in a 3-m high dropshaft model (Rajaratnam et al. 1997), up to 40 in an 8-m high dropshaft (Camino et al. 2015) and about 160 in a prototype dropshaft of 25 m high (Zhang et al. 2016). Due to the large drop height of the dropshaft, the water will disintegrate into small drops after a certain falling distance. These drops dramatically increase the air/water interaction area, which results in a significantly stronger drag force imposed on the air by the water. This momentum transfer from the falling drops to the air phase is considered as the major mechanism of air entrainment in the dropshaft. Besides, the impingement of the water jet on the dropshaft wall and the bottom pool, the water veil flowing along the wall, and the turbulent outflow can also contribute to the air entrainment (Ervine 1998; Chanson 2004a, 2007).

To reduce the amount of air entrainment in plunging type dropshafts, various designs of dropshaft have been reported. Granata (2016) proposed the design of a dropshaft cascade, which had a much lower air demand than a common dropshaft with the same drop height. Dropshaft with a center vertical partitioning wall dividing the drop structure into a ‘dry side’ and a ‘wet side’ was reported in Anderson & Dahlin (1968), Williamson (2001) and Margevicius et al. (2009). However, these works mainly focused on the flow patterns, energy dissipation and water pressure fluctuation with little attention to the air movement in the dropshaft. Wei et al. (2017) conducted preliminary work assessing the air demand, the air circulation and the air pressure variation in the dropshaft with a divider, where internal air circulation was formed. However, their experiments were conducted with a downstream pressure close to the atmospheric pressure while the boundary conditions in actual sewer systems can be varied.

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The performance of the dropshaft was found to be affected by the boundary conditions. Christodoulou (1991), Arao et al. (2012), Carvalho & Leandro (2012) and Zheng et al. (2017) reported that the boundary conditions, e.g. slope and the diameter of the inflow/outflow pipes, or the downstream water depth, could affect the flow feature in the drop manhole and thus affect the energy dissipation. Granata et al. (2014) found that a U-shape bottom could result in a lower energy dissipation for drop manholes than a flat bottom. Swaffield & Jack (1998) changed the boundary condition of a building drainage stack by inserting orifice plates of various sizes, which caused a significant difference in the entrained air flow rate and the air pressure in the stack. Ma et al. (2016) reported that the air entrainment of a plunging type dropshaft under a pressurized downstream condition was much smaller than that under atmospheric pressure. Dropshafts in real sewer systems typically operate under a pressurized downstream condition (Guo et al. 2018). Also, there is usually limited air supply from the top opening as the manhole covers can be sealed to stop odour being released from the sewer system (Ma et al. 2017), and an inadequate air supply would increase the risk of choking (Granata et al. 2015). The boundary conditions can be important to the design and the application of the dropshaft with an internal divider. However, there have been few studies on the effects of the boundary conditions on the performance of the dropshaft with an internal divider, especially on its external air entrainment and internal air circulation.

The main objective of this study is to investigate the air entrainment and the internal air circulation of the dropshaft with a divider under different downstream conditions and air inlet conditions. Experiments were conducted with a large physical model of 7.7 m high. The air flow rates induced from the outside and circulated inside the dropshaft were measured. The response of the air pressure in the dropshaft to different boundary conditions was also analyzed. Additionally, the effectiveness of the internal air circulation on reducing the air entrainment of the dropshaft was assessed.

EXPERIMENTS

A dropshaft model made of Plexiglas with a drop height of \(H = 7.72\) m and a diameter of \(D_s = 0.38\) m was used in this study, as shown in Figure 1(a). The top of the dropshaft was sealed and an air inlet of 10 cm diameter was opened near the top. Water was pumped to the inlet pipe which had a diameter of \(D_i = 0.19\) m and a length of about 12\(D_i\). The diameter of the outlet pipe was \(D_e = 0.38\) m, the same as the dropshaft diameter. The outlet pipe was connected

![Figure 1](https://iwaponline.com/wst/article-pdf/2017/2/441/217090/wst2017020441.pdf)
with the dropshaft by an elbow junction. It was about 2 m long with its end open to the atmosphere. Water was drained directly to the downstream sump by free falling. An internal divider was placed in the middle of the dropshaft which separated the dropshaft into the wet shaft and the air shaft. There was a 0.1-m-diameter opening on the top of the divider for air circulation, as shown in Figure 1(b). The lower end of the divider was about 0.77 m above the dropshaft bottom. As the air pressure increases from top to bottom in the wet shaft caused by the falling water (Ma et al. 2016), the air transported to the dropshaft bottom by the falling water can be partially circulated back to the top of the dropshaft through the air shaft due to the pressure difference.

In the experiments, the dropshaft with the internal divider under different boundary conditions were tested, as listed in Table 1. Case A is when dropshaft is under its original operation condition. As the air space of the downstream sewer is usually pressurized, experiments were also conducted with a weir in the outlet pipe to create a pressurized downstream condition. The weir was installed right after the elbow connection on the outlet, as illustrated in Figure 1(a). The weir blocked the air passage in the outlet pipe and thus created a pressurized downstream condition. Two weir heights of 1/3De and 1/2De, denoted as Cases B1 and B2, respectively, were tested to form downstream blockage of different degrees and thus a different downstream pressurized condition. Experiments were also conducted with the air inlet partially and fully covered, which are denoted as Cases C1 and C2, respectively. Eight water discharges varying from 4.3 to 47.7 L/s were tested which are denoted as Cases C1 and C2, respectively. Eight weir heights of 1/3De and 1/2De, denoted as Cases B1 and B2, respectively, were tested to form downstream blockage of different degrees and thus a different downstream pressurized condition. Experiments were also conducted with the air inlet partially and fully covered, which are denoted as Cases C1 and C2, respectively. Eight water discharges varying from 4.3 to 47.7 L/s were tested in each case. The inflow was subcritical with a steady free surface in the inlet pipe when Qw = 4.3–26.0 L/s, with the Froude number of 0.82–0.94. When Qw ≥ 38.5 L/s, the inlet pipe was full.

In the experiments, the air flow rate induced from the air inlet and that circulated from the air shaft to the wet shaft were measured by a rotating vane anemometer (TSI VelociCalc Model 5725). The sampling frequency of the anemometer was 1 Hz and the total sampling time was 300 s as suggested by Camino et al. (2013). The air pressure variation along the dropshaft was measured by pressure transducers (Model 264 Differential Pressure Transducer, Setra Systems Inc.), which were installed at seven locations from z = 0.64 m to 6.64 m with a spacing of 1 m (denoted as P1–P7 from top to bottom, as shown in Figure 1(a)). Here, z is the falling distance from the invert of the inlet pipe. Pressure transducers were also installed above the inlet pipe at z = −0.72 m (P0) and on the outlet pipe about 1 m away from the elbow junction (P8). In the air shaft, transducers were installed at z = −0.5 m (PA1), 2.64 m (PA2) and 6.56 m (PA3) (see Figure 1(a)). For the air pressure measurement in the wet shaft, small covers with a downward opening were added around the pressure taps on the dropshaft wall, to protect them from being blocked by the falling water. The sampling frequency of the pressure transducers was 250 Hz and the recording time was 24 s for each test. The pressure data were recorded simultaneously by LabVIEW, together with the water flow rate measured by a magnetic flow meter.

### ORIGINAL OPERATION CONDITION (CASE A)

In the experiments, the inflow impinged on the divider shortly after it entered the dropshaft. After the impingement, a portion of the water fell clinging to the divider and the dropshaft wall, while the other bounced away from the divider and fell freely in the air space of the dropshaft. The outflow was strongly turbulent and highly aerated. When there was no weir installed in the outlet pipe, no pool was formed in the bottom of the dropshaft.

When the dropshaft was under the original operation condition (Case A), i.e. no weir was installed in the outlet pipe and the air inlet was fully open, the average air pressure in the wet shaft at Qw = 11.8, 26.1 and 38.5 L/s are plotted in Figure 2 (data from Wei et al. 2017). It increases gradually from P1 to P7. As the water flow rate increases, the magnitude of the negative air pressure increases significantly, which reaches P1 = −641.5 Pa at Qw = 38.5 L/s. The air pressure difference among P1, P2 and P3 is small. Below P3, the air pressure increases almost linearly with a much larger pressure gradient, which has been named as the ‘linear zone’ in Wei et al. (2017). The air pressure gradient in the linear zone increases with the water flow rate.

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**Table 1 | Experimental conditions**

<table>
<thead>
<tr>
<th>Tests</th>
<th>Downstream weir</th>
<th>Air inlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original operation condition</td>
<td>Case A</td>
<td>No weir</td>
</tr>
<tr>
<td>Pressurized downstream</td>
<td>Case B1</td>
<td>With a weir of 1/3De, high</td>
</tr>
<tr>
<td>conditions</td>
<td>Case B2</td>
<td>With a weir of 1/2De, high</td>
</tr>
<tr>
<td>Reduced air inlet</td>
<td>Case C1</td>
<td>No weir</td>
</tr>
<tr>
<td>conditions</td>
<td>Case C2</td>
<td>No weir</td>
</tr>
</tbody>
</table>
In this case, the air pressure in the outlet pipe is close to the atmospheric pressure under all the testing flow rates.

The air flow rate induced through the air inlet $Q_{ai}$ is plotted in Figure 3(a). It shows that the induced air flow rate increases monotonically with the water flow rate. The air flow rate circulated from the air shaft to the wet shaft $Q_{ac}$ is shown in Figure 3(b), which increases from 43.7 L/s to 76.2 L/s as the water flow rate increases from $Q_{w} = 4.3$ L/s to 26.1 L/s while it drops gradually as $Q_{w}$ further increases. The total air demands of the dropshaft $Q_{at}$, i.e. $Q_{at} = Q_{ai} + Q_{ac}$, can be obtained from Figure 3. The ratio of the circulated air flow rate and the total air demand $Q_{ac}/Q_{at}$ is calculated to vary in a range of 0.29–0.43 in Case A.

**Air pressure drop near the inflow impinging position**

From Figure 2, a significant pressure drop can be observed from P0 to P1, the points above and below the inflow impinging position (see Figure 1(a)), especially at large water flow rates. This pressure drop is due to the blockage caused by the impingement of inflow on the divider, which results in the energy loss and pressure drop as the air flow passing through the impinging position. The pressure drop $P_{0}-P_{1}$, non-dimensionalized by the averaged air velocity head in the shaft, is plotted with the dimensionless flow rate $Q^* = Q_{aw}/(gD^*_{s}^{0.5})$ in Figure 4(a), where $D_{s} = 0.265$ m is the equivalent diameter of the wet shaft. Based on Ma et al. (2016), the water fraction in the wet shaft is less than 10% even under the maximum testing flow rate of $Q_{aw} = 47.7$ L/s. To simplify the analysis, the average air velocity inside the wet shaft $V_{a}$ is calculated as $V_{a} = Q_{at}/A$ (A is the cross-section area of the wet shaft).

From Figure 4(a), it can be found that the dimensionless pressure difference $(P_{0} - P_{1})/((1/2)\rho_{a}V_{a}^{2})$ increases significantly with the water flow rate. When $Q^* < 0.1$, the air pressure difference is small. It then reaches over 60 at $Q^* = 0.34$, indicating a large air pressure difference $P_{0} - P_{1} = 460$ Pa that is of the same magnitude as the negative pressure at P1. Notice that $(P_{0} - P_{1})/((1/2)\rho_{a}V_{a}^{2})$ represents the head loss coefficient when air passing through the impinging position. At large water flow rates, the air passage at the impinging position becomes narrower, which makes it more difficult for air to pass through. The significant reduction of the air passage will result in a large value of $(P_{0} - P_{1})/((1/2)\rho_{a}V_{a}^{2})$. As shown in Figure 4(a), the
loss can be estimated as wet shaft area in the impinging region, and thus the energy ratio of the narrowest cross-section of the air passage to the tension. A dimensionless parameter combination of a sudden contraction and a subsequent expansion is introduced here as the ratio of the narrowest cross-section of the air passage to the wet shaft area in the impinging region, and thus the energy loss can be estimated as \( P_0 - P_1 = (1/2)\rho_a K_1 (Va/\alpha)^2 \). Here \( K_1 = (1/2)(1 - \alpha) + (1 - \alpha)^2 \) is the sum of the loss coefficients for a sudden contraction and an expansion (Blevins 1984). Therefore, it yields

\[
\frac{P_0 - P_1}{(1/2)\rho_a V_a^2} = \frac{3}{2\alpha^2} - \frac{5}{2\alpha} + 1
\]

Combining Equations (1) and (2), the contraction ratio of air passage \( \alpha \) under a specific water flow rate \( Q^* \) in the current experiments can be obtained, as plotted in Figure 4(b). It can be seen that \( \alpha \) decreases with \( Q^* \). Small values of \( \alpha \) at large flow rates indicate a large occupation of water at the impingement position, which causes a large pressure drop from P0 to P1. It should be mentioned that \( \alpha \) is defined as a contraction factor in a conceptual but not in a physical sense. Moreover, Figure 4(b) is plotted based on the correlation of \( (P_0 - P_1)/(1/2)\rho_a V_a^2 \) and \( Q^* \) in the current experiments, but it is site specific and can vary for the dropshafts of different sizes and inlet arrangements.

**PRESSURIZED DOWNSTREAM CONDITIONS (CASES B1 AND B2)**

In Cases B1 and B2, the weir blocked the air passage in the outlet pipe, and thus caused the increase of air pressure at the downstream of the dropshaft. The appearance of the outflow with the weir was highly turbulent and aerated. The average air pressure variations along the wet shaft in Cases B1 and B2 are presented in Figure 2. At \( Q_{w1} = 11.8 \text{ L/s} \), the air pressures in Cases A, B1 and B2 are similar, which shows that the installation of the weir has a limited effect on the air pressure at small water flow rates. The air pressure in Case B1 keeps negative under all the testing flow rates, the same as in Case A. However, positive air pressure appears near the bottom of the dropshaft in Case B2, with \( P_0 = 71.5 \text{ Pa} \) and \( P_7 = 177.1 \text{ Pa} \) at \( Q_{w1} = 26.1 \text{ L/s} \), and \( P_6 = 71.5 \text{ Pa} \) and \( P_7 = 279.6 \text{ Pa} \) at \( Q_{w1} = 38.5 \text{ L/s} \). Thus, the higher \( 1/2D_e \) weir has a more significant effect on pressurizing the air phase downstream of the dropshaft.

The air flow rate induced through the air inlet and circulated from the air shaft to the wet shaft in Cases B1 and B2 are shown in Figure 3. For Case B1, with the \( 1/3D_e \) weir, the induced air flow rate and the circulated air flow rate increase monotonically with the water flow rate, which are similar to the Case A. The induced and

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**Figure 4**

(a) Dimensionless pressure drops from P0 to P1 near the inflow impingement area. (b) Variation of the contraction ratio with the dimensionless water flow rates.

The relationship between \((P_0 - P_1)/(1/2)\rho_a V_a^2\) and \(Q^*\) can be correlated by

\[
\frac{P_0 - P_1}{(1/2)\rho_a V_a^2} = 655.4 Q^* - 40.5 Q^* + 2.9 (R^2 = 0.9998)
\]

Similar air pressure drop around the inflow impingement position was observed in building drainage stacks, e.g. Cheng et al. (2005) estimated the air pressure below the impinging position as \( P = K(1/2)\rho_a V_a^2 \) with \( K = 305.2Q^* + 17.3Q^* \). It is similar to Equation (1), with the difference likely due to the actual pipe arrangements.

A simplified model is developed to explain this air pressure drop by modeling the air flow passing through the combination of a sudden contraction and a subsequent expansion. A dimensionless parameter \( \alpha \) is introduced here as the ratio of the narrowest cross-section of the air passage to the wet shaft area in the impinging region, and thus the energy loss can be estimated as \( P_0 - P_1 = (1/2)\rho_a K_1 (Va/\alpha)^2 \).

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circulated air flow rates in Case B2, with the 1/2Dw weir, are close to those in Cases A and B1 at Qw ≤ 11.6 L/s. However, the difference becomes significant as the water flow rate increases to Qw ≥ 18.7 L/s, when positive air pressure occurs at the base of the dropshaft in Case B2. The externally induced air flow rate in Case B2 drops dramatically to less than 40 L/s and keeps around this level when Qw ≥ 18.7 L/s, less than half of those in the other two cases. On the other hand, the circulated air flow rate increases to about 130 L/s, much larger than those of 60–80 L/s in Cases A and B1. It can be seen from Figure 3 that in Case B2, Qa shows a relatively high value at Qw = 38.5 L/s, while Qa is relatively low. It should be noted that the variation of the circulated air flow rate with the increase of water flow rate is determined by the two opposite effects: the increase of pressure difference along the wet shaft and the increase of the head loss. Thus, it is possible that Qa at Qw = 38.5 L/s is smaller than that at Qw = 33.6 L/s when the effect of the increase of the head loss is more significant. The entrained air flow at the air inlet Qa is determined by the negative air pressure at the top of the dropshaft (P0). Similarly, as the pressure gradient in the wet shaft and the pressure drop at the impinging position both increase with the water flow rate, it is possible that Qa at Qw = 38.5 L/s is larger than that at Qw = 33.6 L/s when the effect of the increase of the pressure gradient is more significant. From Figure 3, the ratio of the circulated air flow rate and the total air demand is calculated to be Qc/Qo = 0.40–0.46 in Case B1 while it can be as high as 0.78 in Case B2 with a positive downstream pressure over 200 Pa. The results show a significant effect of the pressurized downstream condition on reducing the air entrainment and increasing the internal air circulation of the dropshaft.

Effectiveness factor

To assess the effectiveness of the internal air circulation on reducing the air entrainment of the dropshaft, a dimensionless ‘effectiveness factor’, (Qc/Qo)/(Qa/Qw), is introduced in this study. Qc/Qo is the ratio of the circulated air flow rate and the total air demand whereas Qa/Qw is the relative air demand of the dropshaft. At a same water flow rate, a larger value of the effectiveness factor indicates a more significant effect of the internal air circulation. For example, at Qw = 18.7 L/s, the air flow rates induced through the air inlet in Cases A, B1 and B2 are 101.6, 95.8 and 51.8 L/s, respectively. The circulated air flow rates in these cases are 75.1, 77.5 and 105.0 L/s, respectively. It can be seen that the dropshaft in Case B2 entrains the least air but circulates the maximum amount of air. The effectiveness factors are calculated to be 0.08, 0.09 and 0.24 for Cases A, B1 and B2, which indicates that the effect of the internal air circulation is most outstanding in Case B2.

The effectiveness factor can also be applied in scenarios with different water flow rates. For example, with a similar relative air demand Qa/Qw ≈ 5.0 in Cases A, B1 and B2, the effectiveness factors are calculated to be 0.10, 0.14 and 0.24, respectively, which indicates that the effect of the internal air circulation in Case B2 is the most outstanding. In these cases, the water flow rates, air flow rate entrained from the air inlet and circulated inside the dropshaft are Qw = 47.4, 38.4 and 18.7 L/s, Qa = 140.9, 112.2 and 51.8 L/s, and Qc = 56.4, 80.2 and 101.6 L/s, respectively. According to these experimental data, it can be concluded that among these cases with a similar relative air demand, Case B2 has the smallest external air entrainment and the effect of internal air circulation is the most significant. It is consistent with the indication of the effectiveness factor. Therefore, it is proper to use the effectiveness factor as a tool to quantify the effect of the internal air circulation on reducing the air entrainment of the dropshaft with a divider.

The effectiveness factors (Qc/Qo)/(Qa/Qw) in Cases A, B1 and B2 are plotted with the relative air demands Qa/Qw in Figure 5. Based on Figure 5, it can be found that the effect of the internal air circulation is more significant in Case B2 compared to the other two cases. Therefore, the internal air circulation formed by the divider will be more efficient in reducing the air entrainment of the dropshaft under a pressurized downstream condition.
REDUCED AIR INLET CONDITIONS (CASES C1 AND C2)

The effect of the air inlet condition on the internal air circulation of the dropshaft with a divider was studied by changing the size of the air inlet: it was reduced by half in Case C1 and completely blocked in Case C2. The other experimental conditions of these two cases are the same as Case A.

The average air pressures in the wet shaft in Cases C1 and C2 are shown in Figure 6(a). Similar to Case A, the air pressure from P1 to P3 keeps almost constant and the linear zone can also be observed in Cases C1 and C2. However, the magnitude of the negative air pressure in Cases C1 and C2 is much larger than that in Case A. The air pressure gradients of the linear zone in Case C2 among these three cases are the largest. The average air pressures in the air shaft in Cases C1 and C2, as well as Case A, are shown in Figure 6(b), including those measured at P7, PA3, PA2, PA1 and P0, along the route of the internal air circulation. It can be seen that the air pressure loss from PA3 to PA1 is minor and can be neglected. However, there are two significant pressure drops at the top and the base of the dropshaft. The drop at the top is from PA1 to P0, caused by the head loss when air passes through the circular opening on the top of the divider. The other one is from P7 to PA3, where air passes from the wet shaft to the air shaft at the bottom of the dropshaft. The pressure drop at the base is due to the blockage at the bottom of the dropshaft, which is caused by the water curtain falling along the divider and water splashes on the bottom. From Figure 6(b), the air pressure in the air shaft in these three cases are all negative. Under the same water flow rate, the magnitude of air pressure in Case C2 is the largest. Also, the pressure drops in Case C2 is most significant, which is due to the largest circulated air flow rate.

The circulated air flow rates in Cases C1 and C2 are shown in Figure 7, together with those in Case A for comparison. Compared to Case A, the circulated air flow rates in Cases C1 and C2 are significantly larger, especially under large water flow rates. The amount of the circulated air is determined by the pressure difference between the top and bottom of the dropshaft (P0 and P7). As the water flow rate increases, the air pressure difference between P0 and P7 becomes more substantial and, thus, more air can be circulated inside the dropshaft. However, at large water flow rates, outflow becomes so turbulent that water splashes on the bottom of the dropshaft can block the passage for air entering the air shaft, which can increase the pressure drop at the base. It is the reason for the reduction of the circulated air flow rate at large water flow rates in Figure 7. Considering the significant pressure loss for air circulation at the base
of the dropshaft, a properly large spacing of the divider above the dropshaft bottom is recommended in the design.

It should be noted that for air/water two-phase flow, scale effects are important when extrapolating the laboratory results to prototype scales. However, there is a lack of proper scaling laws for air/water two-phase flows at the current stage. Chanson (2004a, 2004b) reported that there were limitations using Froude similitude for studies of air entrainment, residence times, and mass transfer in the dropshaft. According to Stephenson & Metcalf (1991) and Camino et al. (2015), the air entrainment in small scale models underestimated the air demand in the prototype dramatically. In the dropshafts of different scales, the flow features can be various, like the fraction of water falling clinging to the wall, the breakup of water, and the group effects of drops, which are important to the air entrainment and the air pressure. The effect of the boundary conditions on the performance of the dropshaft with an internal divider needs to be further verified in a prototype dropshaft.

CONCLUSIONS

The current study investigated the external air entrainment and the internal air circulation of a dropshaft with a divider under different boundary conditions. Experimental results with the dropshaft under the original operating condition, pressurized downstream conditions, and reduced-size air entry conditions were reported.

Under the original operation condition, the air pressure in the wet shaft was negative under all the testing water flow rates and the magnitude of the negative pressure increased with the water flow rate. The average pressure was almost constant in the upper section and then increased linearly to the bottom. An air pressure drop was observed around the inflow impinging area in the wet shaft, which was caused by the blockage of the air passage. An empirical relationship between this pressure drop and the water flow rate was correlated. Under the pressurized downstream conditions, formed by installing a weir in the outlet pipe, the air pressure inside the wet shaft became larger and showed a positive downstream air pressure up to 280 Pa. Compared to the original condition, the outside air entrainment was reduced by more than 50%. The internal air circulation increased significantly and it could reach as high as 0.78 of the total air demand with a pressurized downstream condition. The ‘effectiveness factor’, defined as $(Q_a/Q_{a,t})/(Q_{wa}/Q_{wa,t})$, was introduced to measure the effectiveness of the internal air circulation on reducing the air entrainment of the dropshaft. It was found that the internal air circulation would be more effective in reducing the air entrainment of the dropshaft under a pressurized downstream condition that usually occurs in real situations. Under the reduced-size air entry conditions, the circulated air flow rates were found to be much larger than when under the original operation condition.

The results of this study support the application of the dropshaft with an internal divider in real sewer systems. It also points out the significant pressure drop at the impinging position and the base of the dropshaft, which provides important information and tools for the future design/application of the dropshaft with an internal divider.

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