Flow Field Simulation Analysis of Train Siphon Toilet with Variable Pipe Diameter Based on the Investigation of Siphon Performance

Songzhi Yang¹, Yicheng Zhang¹,*, Hassan Hemida², Yu Wang³ and Dejian Ren¹
¹School of Traffic and Transportation Engineering, Central South University, Changsha, China
²School of Civil Engineering, University of Birmingham, Birmingham, UK
³Baotou Railway Vocational & Technical College, Baotou, China

*Corresponding author email: yc.zhang@csu.edu.cn

Abstract. The performance of siphon toilets in trains with varied pipe profiles were investigated. The profiles of the siphon pipe are varied based on the diameter of the pipe along the pipe length. The flushing process was simulated by using CFD method. The starting time, the duration, the siphon mass flow rate, the negative pressure in the siphon pipe were recorded and selected as siphon performance indexes. The results showed that for the same type of siphon pipe, the siphon performance becomes worse with the increase of the maximum pipe diameter as the minimum pipe diameter is 45mm. The simulation confirms that the performance of the siphon toilet with the pipe diameter varying from large to small then to large is the best; the performance of the siphon with a pipe diameter varying from small to large then to small is the worst. The qualitative results may provide some suggestions for relevant industrial designs.

1. Introduction
With the improvement of the requirements for train comfortability, the siphon toilets have been adopted in the washrooms in trains. It is essential to investigate the siphon toilet for achieving the best flushing effect with the least water consumption. Some researches, such as (Zhao et al., 2008), (Guohua et al., 2009) and (Yi, 2007) have been carried out on the performance of the siphon of household toilets. Although their works provide a significance directive to the investigation of the siphon toilet in trains. However, the operating environment of trains was never considered into the boundary conditions. In this paper, four types of siphon toilet with variable pipe diameter along the pipe length are designed. The flushing process of the siphon toilet integrating with the train operating condition is simulated. Finally, the siphon toilets with different types of siphon pipe used in the toilet in the train are compared.

2. Categories of Siphon Pipes
As shown in Fig. 1, a jet siphon toilet consists of a water tank, a seat ring, a flushing cavity, a flushing pipe and a siphon pipe. The sewage of an ordinary train toilet is usually discharged directly into the atmosphere. Thus, the simulation area is extended around the siphon pipe outlet O. This area is subjected to a wind velocity \( v_{\text{wind}} \) from the right as shown in Fig. 1. In order to conveniently change the pipe diameter, the siphon pipe from inlet I to outlet O is divided into two segments of \( IM \) and \( MO \).
while \( M \) stands for the middle section of \( IO \).

### Figure 1. Configuration of the siphon toilet.

According to the current Chinese sanitary ceramic standard (Yi, 2007), the siphon pipe diameter should vary between 45mm and 80mm. In this paper, the maximum diameter of the siphon pipe is marked as \( N \), and the four types of siphon toilet investigated are as follows: 1) LSL: The siphon pipe diameter decreases gradually from the largest (\( N \)) at section \( I \) to the smallest (45mm) at section \( M \) and then increases gradually to the largest at section \( O \). 2) LSS: The diameter of the siphon pipe decreases gradually from the largest (\( N \)) at section \( I \) to the smallest (45mm) at section \( O \). 3) SLS: The diameter of the siphon pipe increases gradually from the smallest (45mm) at section \( I \) to the largest (\( N \)) at section \( M \) and then decreases gradually to the smallest (45mm) at section \( O \). 4) SLL: The siphon pipe diameter increases gradually from the smallest (45mm) at section \( I \) to the largest (\( N \)) at outlet \( O \).

### 3. Simulation Analysis

#### 3.1. Governing Equations

The flow process can be described by the classical mass continuity equation (1)

\[
\frac{\partial \rho}{\partial t} + \nabla (\rho v) = 0
\]

and the momentum equation (2):

\[
\frac{\partial \rho v}{\partial t} + \nabla (\rho v \otimes v) = -\nabla p + \nabla \cdot \tau + \rho g
\]

\( \rho \) represents the density and \( v \) symbolizes velocity. \( \tau \) is the stress tensor. As one of the important exterior driving forces, gravity is considered (see \( \rho g \) term). Since the whole flushing process is instantaneous, no thermal variation is considered. Thus, the energy equation is neglected during the simulation. To ensure the accuracy, the classical double equation \( k - \varepsilon \) model (Launder and Spalding, 1974) is selected to compute the turbulent stress, formulated as,

\[
\begin{align*}
\frac{\partial k}{\partial t} + \nabla (\rho k) - \nabla \left( \mu \frac{\partial k}{\partial x} \right) &= \nabla \cdot \tau - \rho \varepsilon \\
\frac{\partial \varepsilon}{\partial t} + \nabla (\rho \varepsilon) - \nabla \left( \mu \frac{\partial \varepsilon}{\partial x} \right) &= C_{1\varepsilon} \frac{\varepsilon}{k} \left( \nabla \cdot v \right)^2 - C_{2\varepsilon} \rho \varepsilon
\end{align*}
\]

Where \( k \) denotes the turbulent kinetic energy, \( \varepsilon \) demonstrates kinetic energy dissipation coefficient, and \( p \) is pressure.

\[
p = \mu_{\text{eff}} \nabla v (\nabla v + (\nabla v)^T) - \frac{2}{3} v (\mu_{\text{eff}} \nabla v + \rho k)
\]
Standard wall function was used to treat the first layer of cells near to the wall. The SIMPLIC algorithm is chosen as the coupling method between pressure and velocity. The discretization of the momentum, turbulent kinetic energy and turbulent kinetic energy dissipation rate equations are completed by means of the second-order upwind difference scheme (Yi, 2007).

3.2. Simulation Strategies

3.2.1. Boundary Conditions
Air is chosen as the primary phase (Zhao et al., 2008). In general, there should be some water in the water tank to flush the toilet and some sealing water in the bend to prevent from the odour. Hence the sealing water in the bend and the water in tank are defined as the initial phase. A volume of fraction model with free surface is chosen as the flow model (Xiaotao et al., 2007). The inlet of the water tank and the flushing cavity are defined as pressure inlet, the right side and the left side of the extension area as velocity inlet and pressure outlet respectively, as shown in Fig.2. The pressures of all the boundaries are set as zero. The relative wind velocity is set as 33m/s when a train runs at 120 km/h.

3.2.2. Grid Generation
The model is divided into four zones with different density, as shown in Fig.2. The grids in the flushing cavity and siphon pipe are denser than those in the other regions. The grids are combinations of triangular and quadrilateral. The total number of grids is 101112.

![Figure 2. Illustration of mesh and boundary conditions.](image)

3.3. Criterion of siphon performance
(Guohua et al., 2009) found out that the earlier the siphonage begins in the flushing, the better the siphon performance will be. It has been regarded by (Xiaotao et al., 2007) that the moment at which section $M$ is full of fluid is the start of siphonage. However, this view can’t exclude the situation that the flow rate turns to zero when the fluid happens to be at section $M$, then resulting in backflow. Hence, the moment at which the bend of the pipe is fully filled with fluid should be chosen as the start of siphonage (Guohua et al., 2009), as shown in Fig.3 (a). Secondly, in the case where the mass flow rate of the whole fluid is constant, a longer duration of siphonage will mean a better performance (Guohua et al., 2009). The duration of siphonage means the time from the start to the end of siphonage. (Yi, 2007) pointed out that the moment at which the bubble in the bend is too large to flow can be chosen as the end of siphonage, as shown in Fig.3 (b). Thirdly, the negative pressure in the pipe is an important indicator to evaluate siphon performance. It is easier to begin siphonage and to cause fast flow when the suction force caused by the negative pressure in the siphon pipe is large. Finally, the mass flow rate is also an evaluation indicator for siphon performance.
Thus, in this study the siphon performance is assessed by means of such factors as the starting time, the duration, the mass flow rate, and the negative pressure. Effects of the maximum diameter on starting time, duration and mass flow rate are obtained as shown in Fig.4.

(1) Starting time
The variation of starting time of siphonage with the maximum value of pipe diameter \(N\) is shown in Fig.4(a). If the siphonage doesn’t begin, the variation curve won’t be drawn. As shown in Fig.4(a), the siphon toilets with the siphon pipe of SLS and LSS don’t continue with siphonage when the maximum value \(N\) exceeds 50mm. Because the diameter at outlet \(O\) of the siphon pipe of SLS or LSS is invariable with minimum (45mm) and the flowing quantity through the outlet \(O\) is constant. The diameter at section \(M\) increases with the maximum value \(N\), and the bend cannot be filled with the water of constant flowing quantity when the diameter at section \(M\) is large enough, resulting in no siphonage in the siphon toilet with the siphon pipe of LSS or SLS. Also, Fig.4(a) indicates that the siphonage in the siphon pipe of SLL doesn’t occur when \(N\) exceeds 70 mm. On one hand, the diameter at the inlet \(I\) is the smallest, and the flow like a jet is fast enough for the water to pass section \(M\) when the diameter at section \(M\) is smaller than 70mm; on the other hand, the diameter at outlet \(O\) like a tap is greater than those of LSS and SLS, there are greater flowing quantity, resulting in a later ending of siphonage in the siphon pipe of SLL than LSS and SLS when their maximum pipe diameters are increased. Finally, Fig.4(a) shows that the siphonage occurs in the siphon pipe of LSL in the \(N\) range from 45mm to 80mm. That’s because the diameter at section \(M\) of siphon pipe of LSL is the smallest, the bend is easily filled with water. Fig. 4(a) shows also that for the same \(N\) the starting time of siphon pipe of LSL is shortest while that of SLS is longest. Because the toilet with the siphon pipe diameter of SLS at section \(M\) is the largest when \(N\) is the same, its bend is hard to produce siphonage.

(2) Duration
The variation of duration with the maximum pipe diameter \(N\) is showed in Fig.4(b). Because the siphon toilet with the siphon pipe of SLS or LSS doesn’t begin siphonage when the pipe diameter exceeds 50mm as shown in Fig.4(a), both durations of siphonage can be regarded as 0. Fig. 4(b) indicates that the siphonage durations of the four types of toilet decrease with the maximum pipe diameter \(N\) because of the increase in the flowing quantity. For the same \(N\), the durations of siphonage of the toilet with the siphon pipe of LSL are the longest, followed by SLL. This is because the bend of LSL is easily full of water compared with that of SLL.
(3) Mass flow rate
The mass flow rate at section $M$ is monitored during simulation. If the siphon pipe doesn't start siphonage, the mass flow rate will be regarded as 0. There are two groups of variation trends in Fig.4(c). For the first group, the variation trends of mass flow rate in the siphon pipes of both LSL and SLL nearly keep invariable when $N$ is not more than 70mm. The invariable trends are caused by greater negative pressures in their bend than others as shown in table 1. The siphon mass flow rate of SLL turns 0 when $N$ exceeds 70mm because of no siphonage introduced above. For the second group, the siphon mass flow rates in the siphon pipe of both LSS and SLS have the same decreasing trend when $N$ is from 45 to 55mm. Fig.4(c) also indicates that the mass flow rates of LSS and SLS are both less than that in the siphon pipe of LSL. Their decreasing trends and smaller flow rates are caused by smaller negative pressures in their bends.

Taking all parameters of siphon performance discussed above into consideration, it can be found that the siphonage of the four types of toilet all become poor when the $N$ gets larger.

![Figure 5. Flow field of SLL type.](image)

(a) $N=45$  (b) $N=55$  (c) $N=65$  (d) $N=75$

(4) Negative pressure
In Fig.1, $d_o$ and $d_p$ describes the diameter at outlet $O$ and section $P$ respectively. If $LOSS_{P-O}$ represents the pressure loss (Talu, 2016) from section $P$ to $O$, the relative pressure at section $\Delta P$ is obtained by solving the continuity equation and Bernoulli’s equation from the top section $P$ to the outlet $O$.

$$\Delta p = -\rho gh - \rho gh \left( \frac{d_o}{d_p} \right)^2 + LOSS_{P-O}$$

When $N$ equals 55mm, the mean negative pressures at section $P$ are shown in table 1. The mean negative pressure in the siphon pipe of LSL is the maximum, and followed by SLL, LSS and SLS. The reason is that the diameter ratio $d_o/d_p$ of LSL pipe is the largest, followed by SLL, LSS, SLS.

According to Eq. (5), the larger the diameter ratio is, the larger the mean negative pressure is at the section $P$ when neglecting the loss from section $P$ to $O$.

| Pipe type | Pressure/(Pa) |
|-----------|---------------|
| 55SLS     | -978.6        |
| 55LSL     | -2710.4       |
| 55SLL     | -1290.8       |
| 55LSS     | -1000.7       |

Table 1. Average pressure at section $\Delta P$. 
4. Conclusions
For an open outlet of jet siphon toilet employed in trains, two conclusions can be drawn through the above simulation analyses as follows:

(1) As for the similar profile of the siphon pipes, there exists a turning point for the pipe diameter (~45 mm) to obtain an efficient siphonage. The smaller diameter (< 45 mm) can induce better function of siphon pipe compared to larger size (> 45 mm).

(2) Based on current simulations, it is found that the profile of siphon pipe can strongly affect the efficiency of siphonage, thus influencing the flushing performance of toilet. The siphon pipe with the diameter evolving from a large value, then to smaller size and turning to large again has presented better performance. Contrarily, a relatively low efficiency is witnessed if the pipe diameter starts with a small value, grows to a larger one and decreases to a smaller value again.

Since current studies are only concerning simulation, the obtained conclusions and predictions are qualitatively. More convincing results will be explored as combined with related experimental observations. This will be our future work.

References
[1] Guohua, T., Zijian, L., Zhiwei, P., Zhenzhu, L., 2009. The structural parameters optimization of siphon pipe on water closet based on ANN. China Ceram. 5, 38–44.
[2] Launder, B.E., Spalding, D.B., 1974. The numerical computation of turbulent flows. Numer. Predict. flow, heat Transf. Turbul. Combust. 3, 269–289.
[3] Talu, M., 2016. Hydraulic pressure loss in technical piping with annular section, Numerical calculation and C.F.D. Universitaria Publishing house, Craiova, Romania.
[4] Xiaotao, P., Yongsun, S., Jiemin, Z., Li, J., 2007. The Determinant Method of Ceramic Sanitary Ware Forming Siphon Phenomenon Based on VOF Model. Acta Sci. Nat. Univ. Sunyatseni 46, 36–40.
[5] Yi, G., 2007. CFD simulation and experimental investigation on the siphonage-pipeline’s inner flow field. Hunan University.
[6] Zhao, S.Y., Liu, Z.J., Peng, Z.W., 2008. Optimized Design of Toilet Siphon Pipeline Based on Fluent and Its Validated Test. J. Syst. Simul. 29, 33–35.