Study on the Influence of Toilet Siphon Pipe Shape on Flushing Performance

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Highlights:

- The shape of a toilet siphon pipe was characterized by six shape parameters to facilitate study.
- Under one single shape parameter, a toilet can obtain good flushing performance when the climbing angle, the arc width, the arc height, the pipe diameter, the climbing width, and the climbing height are 48°, 45 mm, 210 mm, 50 mm, 90 mm, and 30 mm, respectively.
- The flushing performance of a toilet is not proportional to the siphon pipe diameter under the condition of the same water consumption.

Abstract. The goal of this work was to explore the influence of toilet siphon pipe shape on flushing performance. The flushing processes of a toilet under different shape parameters were simulated by using computational fluid dynamics (CFD) with a volume of fluid (VOF) multiphase model. The effects of siphon pipe shape on flushing performance were analyzed in detail. The interpretation of the simulation results was experimentally validated. The results reveal that a toilet may obtain good flushing performance under one single shape parameter when the climbing angle, the arc width, the arc height, the pipe diameter, the climbing width, and the climbing height are about 48°, 45 mm, 210 mm, 50 mm, 90 mm and 30 mm, respectively. With the increase of the siphon pipe diameter, the toilet flushing performance peaks in the range between 50 and 53 mm rather than continuing to improve. In order to reasonably evaluate the flushing effect of the toilet, all flow parameters on a characteristic cross section of the siphon pipe, including the average velocity, the average pressure and the average mass flow rate, should be comprehensively considered instead of one single parameter. The findings of this study provide a reference for the pipe shape design of toilets.

Keywords: *CFD; flushing performance; shape parameters; siphon pipe; toilet.*

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1 Introduction

The shape of the siphon pipe is a key factor that affects the flushing performance of siphon toilets and is an important topic for the sanitary wares industry and scientific researchers to improve toilet flushing performance. At present, the shape design of the siphon pipe is mainly based on experimental trial-and-error methods, which lacks theoretical guidance, resulting in a design process that is quite time-consuming and a design quality that is uneven. It is necessary to explore the influence of the shape parameters of the siphon pipe on flushing performance to facilitate the design of the siphon pipe shape.

A number of researchers have carried out both numerical and experimental studies on the flushing performance of toilets. Zhao, *et al*. simulated the flushing processes of a toilet by using CFD to investigate the velocity distribution and pressure distribution inside the siphon pipe. In order to obtain better flow field distribution, the siphon pipe shape was improved by redesigning the local position of the siphon pipe [1]. Although this study improved the flushing effect of the toilet to a certain extent, it did not establish a relationship between the pipe shape parameters and the flushing performance. The change of water velocity during the ball discharge process of the toilet was experimentally analyzed by Cheng and Jhang [2]. The average velocity of the water was approximately obtained by measuring the average velocity of balls by utilizing high-speed camera technology. Ge, *et al*. [3] designed the siphon pipe shape of a toilet by using the Fibonacci sequence and the Lucas sequence for improving the flushing performance. They proposed a new idea for the design of the toilet siphon pipe shape, but the design process was performed based on a fixed overall shape size of the siphon pipe and did not consider the influence of different overall shape sizes on the flushing performance. Cheng, *et al*. [4] studied the effect of three types of siphon pipes on the flushing performance and obtained an improved siphon pipe shape. On the basis of a fixed siphon pipe shape, An, *et al*. [5] proposed a new flexible pipe that can be automatically adjusted during the flushing process. This research showed that the flushing performance of the improved toilet with a flexible pipe was better than that of a toilet with a fixed pipe. Further, An, *et al*. [6] studied the influence of the horizontal length of the siphon pipe and water consumption on the flushing performance. A CFD simulation of the toilet flushing process was conducted by Mahecha, *et al*. [7] to investigate the changes of pressure and mass flow rate for a better understanding of the flushing mechanism.

It can be seen from the above researches that the shape of the siphon pipe has a significant influence on the flushing performance. However, these works mainly focused on local optimization of the siphon pipe based on a fixed pipe shape, and the relationship between the shape parameters of the siphon pipe and the flushing performance is still unclear. Hence, the objective of this study was to carry out a systematic and in-depth research on the relationship between the shape parameters of the siphon pipe and the flushing performance. For this purpose, a series of simulations were performed and the influence of the siphon pipe shape on the flushing performance was analyzed in detail. The correctness of the simulation results was validated by corresponding experimental studies. This work can offer guidance for the selection of shape parameters of the siphon pipe.

2 Numerical Simulation

2.1 3D Simulation Model

A toilet simulation model was built based on the actual shape and size of a jet siphon toilet to ensure that the simulation conditions were consistent with the actual flushing process of the real model, as shown in Figure 1. Although the created toilet model was somewhat simplified, it retained all the structures that affect the water flow [8].

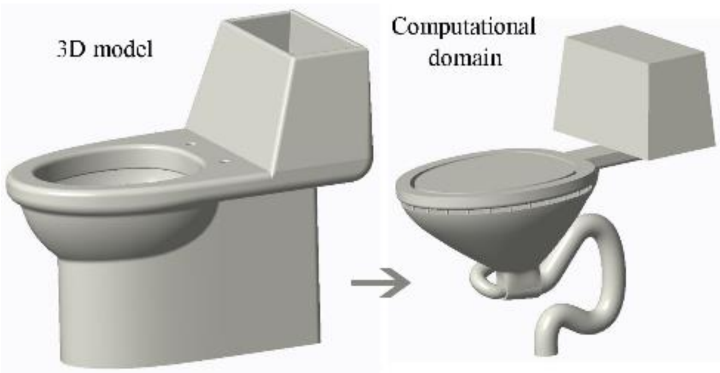

Figure 1 3D simulation model of a toilet.

The shape of the siphon pipe was characterized by six parameters, i.e. A, B, C, D, E and F, as illustrated in Figure 2. The parameters of A, B, C, D, E and F were named climbing angle, arc width, arc height, pipe diameter, climbing width, and climbing height, respectively. L is the height of the water seal of the siphon pipe; this parameter should not be below 50 mm according to the Chinese national standard.

It should be noted that while this study mainly focused on the influence of siphon pipe shape on flushing performance, other structures of the toilet, including the water tank, the seat ring, the bowl and the jet pipe which are also relevant for the toilet flushing efficiency. These were kept constant in order to ensure the same experimental conditions.

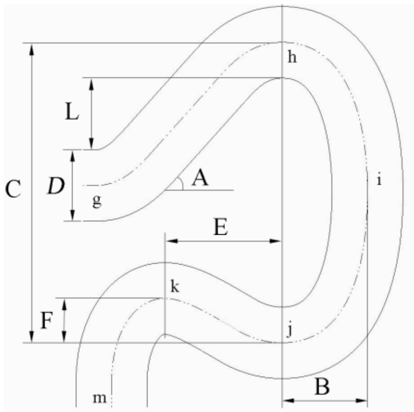

Figure 2 Shape parameters of the siphon pipe.

2.2 Governing Equations

The continuity equation and momentum equation of water flow movement during the flushing process can be written as [9]:

$$\frac{\partial \rho}{\partial t} + \nabla \bullet (\rho U) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho U) + \nabla \bullet (\rho U U) = -\nabla p + \mu \nabla^2 U \tag{2}$$

where U is the velocity field, p is the pressure field, t denotes the time, ρ and μ are the mass density and dynamic viscosity of liquid.

The flushing process of a toilet is a complex flow problem with a free surface. The free surface is the interface between the water and the air. To solve the gas-liquid two-phase flow problem, the volume of fluid (VOF) model has been proposed by Hirt and Nichols in 1981, which is widely used in many fields [10-13]. The function F, which represents the volume fraction of the liquid phase within the grid domain, is used in the VOF model to track the position of the free surface [14-15]. If $F = 1$ the grid is completely occupied by the liquid phase. If $F = 0$ the grid is fully occupied by the air phase. And if $0 < F < 1$ there is not only liquid phase but also air phase in the grid. Assuming any point (x, y, z) in the flow field, the function F (x, y, z, t) can be defined as:

$$F(x,y,z,t) = \begin{cases} 0 & \textit{air phase} \\ 0 \sim 1 & \textit{free surface} \\ 1 & \textit{liquid phase} \end{cases} \tag{3}$$

The function F (x, y, z, t) satisfies the following conservation equation:

$$\frac{\partial F}{\partial t}+(U\bullet\nabla)F=0 \tag{4}$$

The F of each time step can be obtained by solving the above equation and the position of the free surface can be determined by combining the free surface reconstruction algorithm.

The density and dynamic viscosity of two-phase fluid in the grid are given by:

$$\rho = F\rho_{liquid} + (1-F)\rho_{air} \tag{5}$$

$$\mu = F\mu_{liquid} + (1-F)\mu_{air} \tag{6}$$

where ρ_{liquid}, ρ_{air}, μ_{liquid} and μ_{air} are density of liquid, density of air, dynamic viscosity of liquid and dynamic viscosity of air, respectively.

In this paper, the two-equation realizable k-ε turbulence model was used to calculate the flushing process; its applicability has been previously proved [16]. The governing equations of the realizable k-ε turbulence model can be expressed as:

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho k u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}[(\mu+\frac{\mu_t}{\sigma_k})\frac{\partial k}{\partial x_j}]+G_k-\rho\varepsilon \tag{7}$$

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial(\rho\varepsilon u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}[(\mu+\frac{\mu_t}{\sigma_\varepsilon})\frac{\partial \varepsilon}{\partial x_j}]+\rho C_1 E\varepsilon-\rho C_2\frac{\varepsilon^2}{k+\sqrt{\nu\varepsilon}} \tag{8}$$

where σ_k = 1.0, σ_ε = 1.2, C_2 = 1.9, k is the turbulent kinetic energy, ε is the turbulence dissipation rate, μ_t is the turbulent viscosity, G_k is the generation term of turbulent kinetic energy generated by the mean velocity gradient. C_1 = max [0.43, $\eta/(\eta+5)$], $\eta = (2E_{ij}E_{ij})^{1/2}(k/\varepsilon)$. E_{ij} is the mean strain rate, which can be calculated by:

$$E_{ij}=\frac{1}{2}(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}) \tag{9}$$

A detailed description of the realizable k-ε turbulence model can be found in [17].

2.3 Simulation Parameters

In this research, Ansys Fluent was used to simulate the flushing process of the toilet. According to the real-world situation of the flushing process, the boundary conditions of one pressure inlet and two pressure outlets were established, as illustrated in Figure 3. The volume of water in the water tank was 5.5 L. The pressure-based solver was employed to calculate the transient flow process. To track the position of the free surface, the VOF model was adopted. The air and water were set to primary phase and secondary phase, respectively.

The realizable k-ε model was used in this work. Furthermore, the standard wall function was utilized to calculate the near-wall flow and the SIMPLE algorithm was applied to solve the pressure-velocity coupling equations [18]. The residuals, the time step and the total simulation time were set to 10^{-4}, 0.0002 s and 6.6 s, respectively. The simulations were performed on a DELL blade server using an Intel MPI for parallel computing to save computation time [19]. In order to quantitatively analyze the influence of the siphon pipe shape on the flushing performance, a surface M located in the highest part of the siphon pipe was created to record the changes of the flow parameters over time in the entire flushing process, as shown in Figure 3.

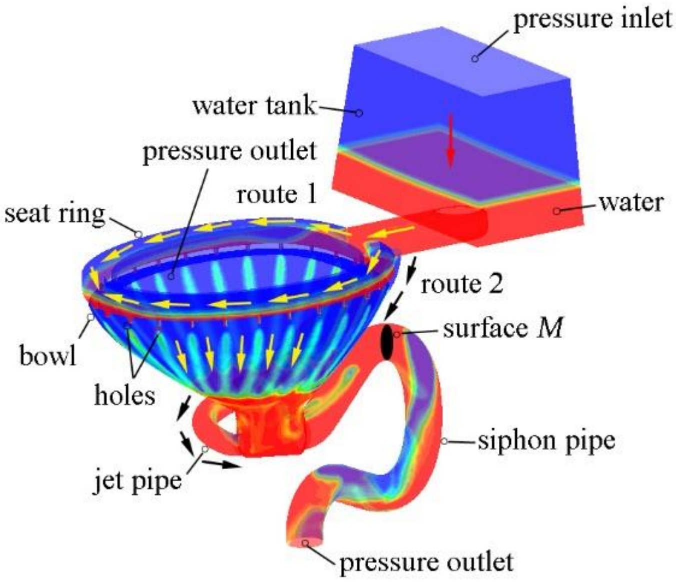

Figure 3 Simulation conditions.

In order to explore the influence of the shape parameters of the siphon pipe on the flushing performance, six groups of simulations were set up.

Table 1 gives the detailed parameter settings for the simulations. In each group of simulations, only one shape parameter was changed while the other shape parameters were kept constant. Moreover, the height of the water seal was set to 50 mm in all simulations.

Table 1 Parameter settings used in the simulation.

Group number	A (°)	B (mm)	C (mm)	D (mm)	E (mm)	F (mm)
1	36, 40, 44, 48, 52	55	210	50	90	30
2	48	45, 50, 55, 60, 65, 70	210	50	90	30
3	48	65	170, 190, 210, 230, 250	50	90	30
4	48	65	210	44, 47, 50, 53, 56, 59	90	30
5	48	65	210	50	60, 70, 80, 90, 100, 110	30
6	48	65	210	50	90	10, 20, 30, 40, 50, 60

2.4 Grid Independence Analysis

During the flushing process there are two routes of the water flowing from the water tank to the siphon pipe, as indicated by the arrow in the Figure 3. The first flow route of the water is water tank-seat ring-holes-bowl-siphon pipe and the second flow route of the water is water tank-seat ring-jet pipe-siphon pipe. Although the object of this study was to explore the influence of the siphon pipe shape on the flushing performance, the other parts, including the water tank, the seat ring, the holes, the bowl and the jet pipe, were also included in the computational domain in order to simulate the complete flow process of the water from the water tank to the siphon pipe.

The computational domain of the toilet was meshed by utilizing the ICEM CFD (Integrated Computer Engineering and Manufacturing Code for Computational Fluid Dynamics) software. According to the shape features of the computational domain, the water tank was meshed with structured grids, while other parts were meshed with unstructured grids. In order to determine a reasonable grid size, a grid independence verification was performed.

In this paper, four group simulations with different grid sizes were conducted to investigate the influence of the number of grid cells on the stability of the numerical model. For the convenience of analysis, the variations of the mass flow rate on surface *M* in different groups were recorded, as depicted in Figure 4.

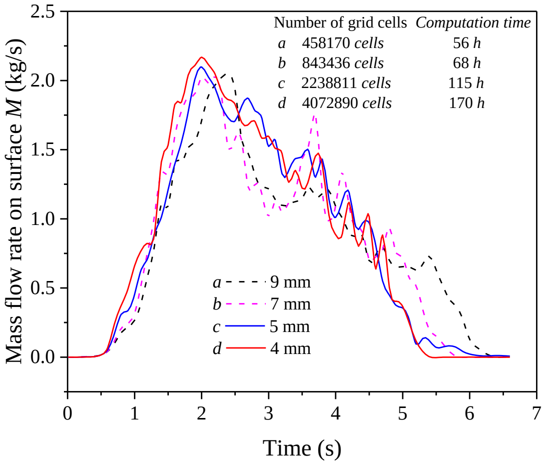

Figure 4 Effect of the number of grid cells on the stability of the numerical model.

It can be seen from Figure 4 that the fluctuation of the simulation results was continuously getting smaller along with the reduction of the grid size, which means that the computational accuracy gradually improved. By comparing group *c* with group *d* it can be noticed that the calculation results of the two groups had only minor differences. However, the number of grid cells and computation time increased rapidly when the grid size was changed from 5 mm to 4 mm, which means that a small grid size will lead to a heavy computation load. Overall, the calculation results of group *c* are acceptable by taking computational accuracy and computational cost into account. Based on the analysis above, the grid size was determined at 5 mm for this study.

3 Results and Discussion

3.1 General

Surface *M* (shown in Figure 3) was selected to record the changes of the flow parameters over time. This position is a key cross section of siphon generation, where the flushing performance of a toilet can be reflected by the values of the flow parameters [16,20]. During the flushing process, the flow parameters on surface *M* change over time. In order to obtain the flow parameter values at different times, the area-weighted average velocity magnitude, the mass flow rate and the area-weighted average static pressure on surface *M* were automatically exported every 0.01s during the simulation process. Subsequently, the average values of the exported flow data were calculated from the beginning of the flushing process until the flow parameters were back to the same condition to characterize the overall flushing performance of the toilet under different shape parameters.

The calculated average values of the area-weighted average velocity magnitude, the mass flow rate and the area-weighted average static pressure were called the average velocity, the average mass flow rate and the average pressure for convenience of description. The larger the average velocity and the average mass flow rate, the lower the average pressure and the better the overall flushing performance. In this section, the changes of average velocity, average pressure and average mass flow rate under different shape parameters are analyzed in detail to explore the effect of the siphon pipe shape of a toilet on the flushing performance.

3.2 Influence of Climbing Angle on Flushing Performance

The climbing angle is an important parameter that affects the flushing performance of a toilet. The larger the climbing angle, the shorter the length of curve g-h. The impacts of the climbing angle on the average velocity, the average pressure and the average mass flow rate on surface *M* are depicted in Figure 5.

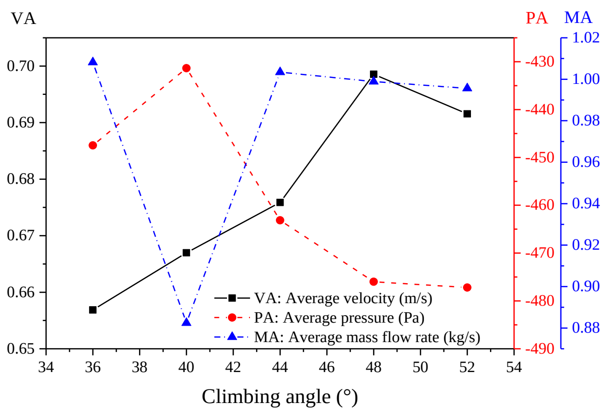

Figure 5 Influence of climbing angle on the flow parameters.

It is obvious from Figure 5 that the average velocity first increases and then decreases with the increment of the climbing angle. When the climbing angle is about 48°, the average velocity reaches its peak value. In this situation, both the average pressure and the average mass flow rate have better values, which means that the toilet may obtain good flushing performance at this time. Moreover, the average pressure initially increases and then decreases and obtains its minimum value at a climbing angle of 52°. In this case, however, neither the average velocity nor the average mass flow rate reaches the ideal value. This is mainly because the oversized climbing angle increases the local losses of water flow from point g to point h inside the siphon pipe, resulting in a weaker flushing performance.

Therefore the climbing angle should not be too large to get an optimal flushing effect. Furthermore, when the climbing angle is around 36°, the average mass flow rate acquires the maximum value, but the average velocity and the average pressure are poor. When the climbing angle is at a lower value, the length of curve g-h is longer, which brings about that the siphon effect formed inside the siphon pipe is unstable and insufficient. Although the local losses of water flow are small at this time, the overall flushing performance is not strong.

It can be concluded from the above analysis that the comprehensive flushing performance of a toilet is optimal when the climbing angle is 48°. On the whole, the flushing performance of a toilet with a larger climbing angle (e.g. 48° or 52°) is better than that of a smaller climbing angle (e.g. 36° or 40°), as shown in Figure 5.

3.3 Influence of Arc Width on Flushing Performance

The arc width determines the curvature and the length of curve h-i-j. Figure 6 shows the influences of the arc width on the average velocity, the average pressure and the average mass flow rate on surface *M*. It is clear from Figure 6 that the average velocity, average pressure and average mass flow rate all get better values when the arc width is 45 mm and 65 mm, which indicates that the toilet may obtain good flushing performance under these two conditions.

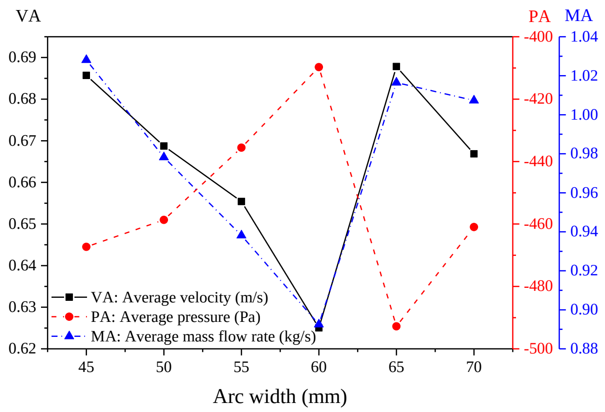

Figure 6 Influence of arc width on the flow parameters.

When the arc width is 45 mm, the length of curve h-i-j is the shortest. At this time, the water flow can fill the siphon pipe quickly and form a stable siphon in a short time, so the flushing performance is strong. When the arc width is 65 mm, the length of curve h-i-j is longer, which delays the formation of the siphon effect. In this condition, however, the curvature of the siphon pipe may be reasonable, which results in a decrease of flow resistance and an increase of siphon duration. Therefore, the toilet can also get a better flushing effect under this shape parameter.

3.4 Influence of Arc Height on Flushing Performance

The arc height has a great influence on the flushing performance of a toilet, so it is necessary to obtain an appropriate arc height for getting a good flushing effect. Figure 7 presents the relationships between the arc height and the average values of the flow parameters. From Figure 7, it can be observed that when the arc height is about 210 mm, the average velocity and the average mass flow rate reach the maximum values and the average pressure reaches the lowest value, which suggests that the toilet may achieve the best flushing performance under such a condition.

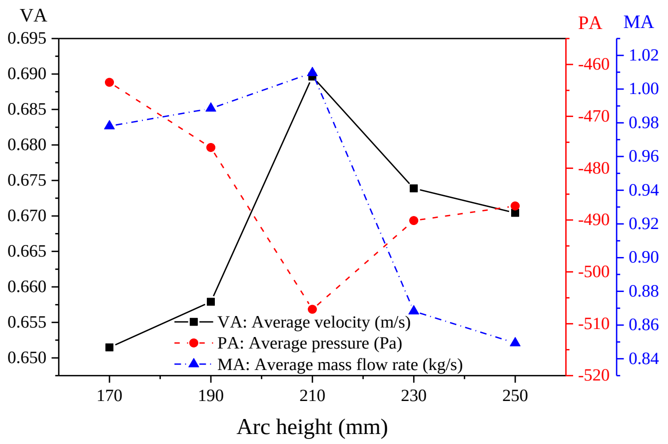

Figure 7 Influence of arc height on the flow parameters.

When the arc height at a lower value, the vertical height of curve h-j is smaller, resulting in the siphon effect occurring inside the siphon pipe being insufficient. This is the reason why the flushing performance is relatively poor under this condition. Furthermore, when the arc height is too large, the flushing performance is not strong. The explanation for this is that with a large vertical height of curve h-j the siphon is stable only for a short time, yielding a poor flushing performance. Therefore, the arc height should be set to 210 mm when we design the shape of the siphon pipe to obtain a good flushing performance. An arc height that is too small or too large is not conducive to the improvement of the arc height flushing effect.

3.5 Influence of Pipe Diameter on Flushing Performance

The effects of pipe diameter on the flow parameters are illustrated in Figure 8. With the increment of the pipe diameter, the average velocity continuously decreases, the average pressure steadily increases while the average mass flow rate first increases and then decreases. At a lower pipe diameter value, the average velocity is high and the average pressure is low, which indicates that the siphon intensity formed in the pipe is strong. However, a small diameter will give rise to pipe blockage, which is harmful for the improvement of the flushing effect. When the total water consumption is constant, the larger the pipe diameter, the shorter the duration of the siphon effect. Hence, the flushing performance is not good when the pipe diameter has a high value. Figure 8 also shows that the flushing performance is not proportional to the pipe diameter and there is an ideal flushing effect when the pipe diameter changes from a low value to a high value.

It can be concluded from the above analysis and Figure 8 that the toilet can obtain better comprehensive flushing performance when the pipe diameter is in the range of 50 mm to 53 mm.

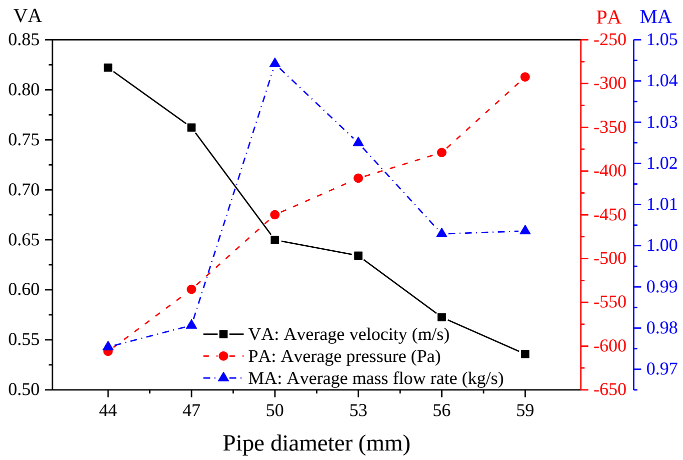

Figure 8 Influence of pipe diameter on the flow parameters.

3.6 Influence of Climbing Width on Flushing Performance

Figure 9 gives the influences of the climbing width on the average values of the flow parameters. As can be seen from Figure 9, the comprehensive flow parameter of the toilet is best when the climbing width is 90 mm, which demonstrates that the flushing performance is probably strongest in this case. When the climbing width is below 90 mm, the inclination angle of curve j-k is larger, which leads to greater flow resistance in the pipe, so the flushing performance of the toilet is bad. Moreover, the flushing performance of the toilet is also poor when the climbing width is too large. This is because an oversized length of curve j-k causes the maintenance time of a stable siphon to become shorter. On the whole, the flushing performance of the toilet at a larger climbing width is better than at a smaller climbing width, as shown in Figure 9.

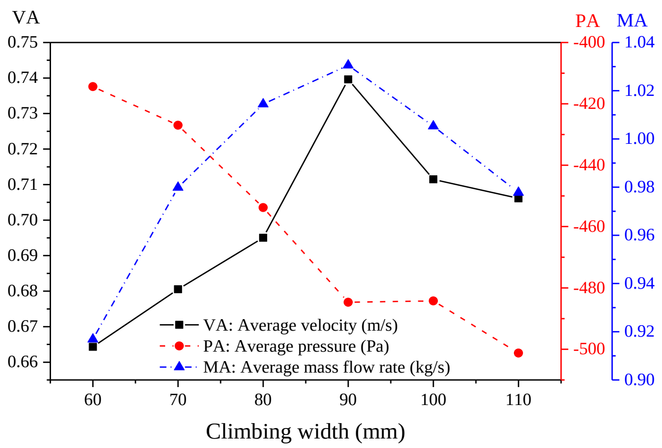

Figure 9 Influence of climbing width on the flow parameters.

3.7 Influence of Climbing Height on Flushing Performance

The climbing height affects the inclination angle and the length of curve j-k and a reasonable climbing height helps to improve the flushing performance of the toilet. Figure 10 shows the relationships between the climbing height and the flow parameters. It is clear that the average velocity, average pressure and average mass flow rate all reach their ideal values when the climbing height is about 30 mm, which reveals that the toilet may have the best flushing performance under such condition.

When the climbing height is less than 30 mm, the inclination angle and the length of curve j-k are smaller, which leads to a lower flow resistance in the siphon pipe, so the flushing performance is relatively good. However, when the climbing height is greater than 30 mm, the flushing performance dramatically decreases. This is because the positive pressure is first formed inside the siphon pipe and is then converted into negative pressure, resulting in weaker siphon intensity.

Therefore, the value of climbing height should not be too large for getting a better flushing performance.

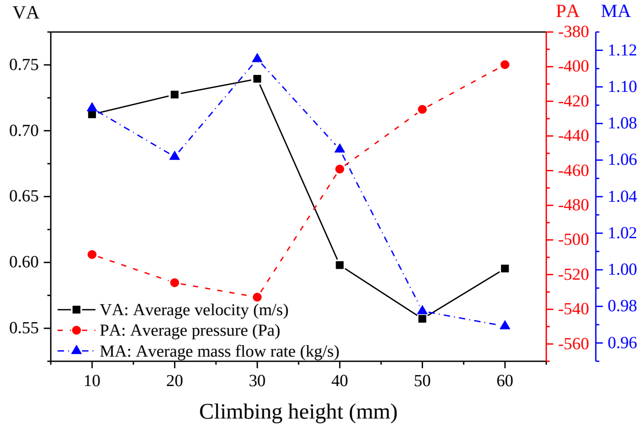

Figure 10 Influence of climbing height on the flow parameters.

4 Experimental Validation

To validate the feasibility of the simulation results, a series of experiments were conducted by using an experimental device whose structural parameters could be adjusted within a certain range, as shown in Figure 11.

Figure 11 Experimental toilet device.

In the experiments, the parameter settings of the siphon pipe were the same as in the simulations, but it should be noted that only partial experiments, i.e. involving the climbing angle, the arc width, the climbing width and the climbing height and three parameters of the arc height, were conducted due to the limitation of the experimental device's size. In order to quantitatively characterize the flushing performance of the toilet, one hundred polypropylene (PP) balls with a diameter of 17.5 mm and a density of 910 kg/m^3 were used to perform flushing experiments. Furthermore, the total volume of water used in experiments was 5.5 L, which was precisely controlled by a flow meter. The flushing efficiency F_η is given by:

$$F_\eta = \frac{B_{out}}{B_{all}} \times 100\% \tag{10}$$

where B_{out} is the average quantity of PP balls that were washed out of the toilet in six sets of experiments, and B_{all} equaled one hundred in each experiment.

The experimental results are shown in Figures 12-16. By comparing Figures 12-16 with Figures 5-10 we can see that the change trends of the flushing performance under different shape parameters in the experiments on the whole were consistent with those of the simulations, which indicates that the influence mechanism of siphon pipe shape on flushing performance can be analyzed deeply by simulation. Based on the simulation and the experimental results, it can be inferred that the flow parameters of a toilet are reasonable when the climbing angle, the arc width, the arc height, the pipe diameter, the climbing width, and the climbing height are 48°, 45 mm, 210 mm, 50 mm, 90 mm and 30 mm, respectively.

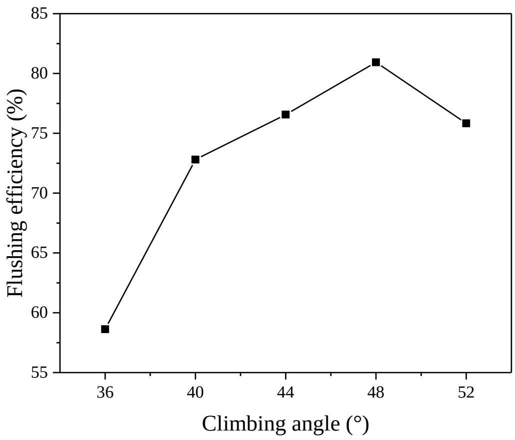

Figure 12 Experimental results under different climbing angles.

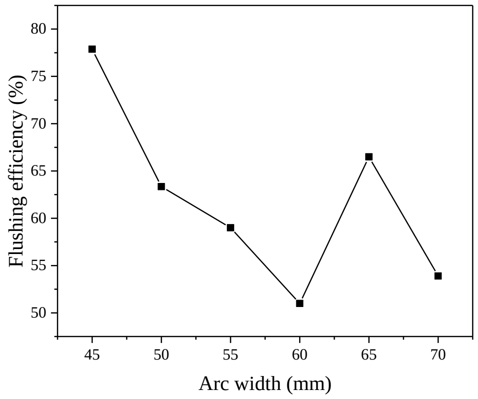

Figure 13 Experimental results under different arc widths.

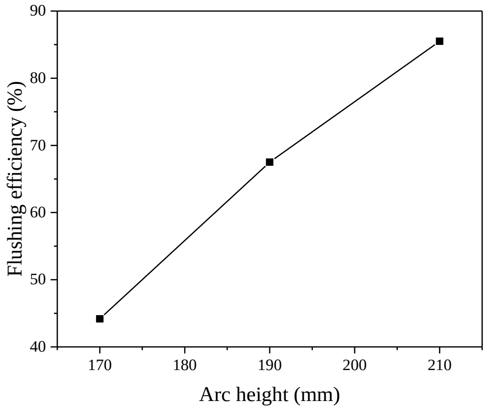

Figure 14 Experimental results under different arc heights.

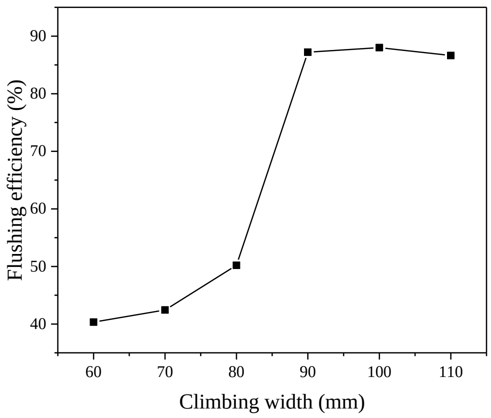

Figure 15 Experimental results under different climbing widths.

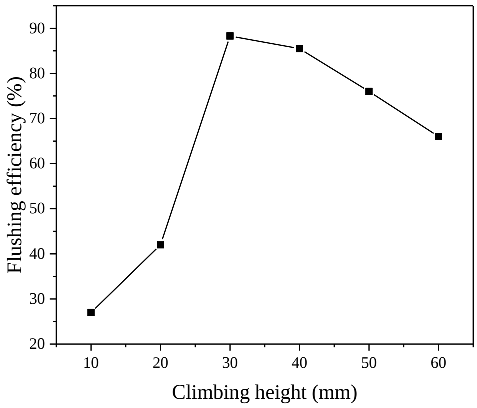

Figure 16 Experimental results under different climbing heights.

From another perspective, the simulation and the experimental results also suggest that the change rules of flushing performance can be better characterized by comprehensive flow parameters than one single flow parameter. Therefore, when evaluating toilet flushing performance, all flow parameters should be comprehensively considered.

5 Conclusions

In this study, a series of simulations and experiments of toilet flushing processes were conducted to explore the influence of the shape parameters of the siphon pipe on flushing performance. The following conclusions can be drawn from the present work:

1. Based on the numerical simulations and experimental validation, a toilet can obtain good values of flow parameters when the climbing angle, the arc width, the arc height, the pipe diameter, the climbing width, and the climbing height are 48°, 45 mm, 210 mm, 50 mm, 90 mm, and 30 mm, respectively.
2. The toilet flushing performance is not proportional to the siphon pipe diameter and peaks in the range between 50 and 53 mm. Good comprehensive flow parameters related to a characteristic cross section (surface *M*) inside the siphon pipe, such as higher velocity, lower pressure and larger mass flow rate, are important conditions for getting better flushing performance. However, obstruction by coarse sediments may be a concern and should be considered. The flushing effect should be reasonably characterized by all flow parameters instead of one single parameter.
3. Note that this study was carried out under one single shape parameter. In order to obtain an optimal shape of the siphon pipe, all combinations (32400) of the six shape parameters need to be studied. However, the total computing

time estimated for the 32400 simulations required is approximately 425 years under the tested conditions and computational means used, which is clearly impossible to complete. In further studies, orthogonal experiments will be conducted and adapted to be able to consider the interactions between the different factors.

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References

[1] Zhao, S.Y., Liu, Z.J. & Peng, Z.W., *Optimized Design of Toilet Siphon Pipeline Based on Fluent and Its Validated Test*, Journal of System Simulation, **20**(16), pp. 4412-4416, 2008. (Text in Chinese and Abstract in English)

[2] Cheng, W.S. & Jhang, C.Y., *Velocity Measurement and Flow Field Simulation of a Sit-type Water Closet*. The 4th International Meeting of Advances in Thermofluids, **1440**(1), pp. 1068-1077, 2012.

[3] Ge, X.L., Wang, H.F., Liu, S.R., Li, Z.F., Tong, X. & Pu, J.F., *Application of Fibonacci Sequence and Lucas Sequence on the Design of the Toilet Siphon Pipe Shape*, Journal of Engineering and Technological Sciences, **51**(4), pp. 463-478, 2019.

[4] Cheng, W.S., Lee, R.T., Liu, C.H. & Hsia, C.W., *A Study on Evacuation Performance of Siphon-Type Water Closets*, The 10th Asian International Conference on Fluid Machinery, **1225**, pp. 75-80, 2010.

[5] An, I.Y., Lee, Y.L. & Kim, J.H., *A Study of the Characteristics of a Super Water-saving Toilet with Flexible Trapway by Measuring Accumulated Flow Rate*, Journal of Mechanical Science and Technology, **28**(8), pp. 3067-3074, 2014.

[6] An, I.Y., Lee, Y.L., Jung, E.D. & Cho, W.S., *A Study on Performance Optimization of a Toilet by Measuring Accumulated Flow Rate of a Trapway*, Journal of Mechanical Science and Technology, **28**(4), pp. 1319-1326, 2014.

[7] Mahecha, J., López, O. & Ardila, O., *Computational Study of the Dynamics of the Flow in a Gravity-driven Toilet*, ASME 2012 Fluids Engineering Division Summer Meeting, pp. 1319-1327, 2012.

[8] Li, W., *Research on CBD-Based Optimization Method and its Application on Toilet*, Master Dissertation, Hunan University, Changsha, 2009. (Text in Chinese and Abstract in English)

[9] Zhang, S.S., *Principle and Application of CFD Technology*, Ed. 1, Huazhong University of Science & Technology Press, 2016.

[10] Hirt, C.W. & Nichols, B.D., *Volume of Fluid (VOF) Method for the Dynamics of Free Boundaries*, Journal of Computational Physics, **39**, pp. 201-225, 1981.

[11] Abbassi, W., Besbes, S., Elhajem, M., Aissia, H.B. & Champagne, J.Y., *Numerical Simulation of Free Ascension and Coaxial Coalescence of Air Bubbles Using the Volume of Fluid Method (VOF)*, Computers & Fluids, **161**, pp. 47-59, 2017.

[12] Wang, Z., Chen, R., Zhu, X., Liao, Q., Ye, D., Zhang, B., He, X. & Jiao, L., *Dynamic Behaviors of the Coalescence Between Two Droplets with Different Temperatures Simulated by the VOF Method*, Applied Thermal Engineering, **131**, pp. 132-140, 2017.

[13] Mohsin, M. & Kaushal, D.R., *3D CFD Validation of Invert Trap Efficiency for Sewer Solid Management Using VOF Model*, Water Science and Engineering, **9**(2), pp. 106-114, 2016.

[14] Yang, Y.T., Wang, Y.H. & Hsu, J.C., *Numerical Thermal Analysis and Optimization of a Water Jet Impingement Cooling with VOF Two-phase Approach*, International Communications in Heat & Mass Transfer, **68**, pp. 162-171, 2015.

[15] Tsui, Y.Y. & Lin, S.W., *Three-dimensional Modeling of Fluid Dynamics and Heat Transfer for Two-fluid or Phase Change Flows*, International Journal of Heat & Mass Transfer, **93**, pp. 337-348, 2016.

[16] Wang, Y.H., Xiu, G.J. & Tan H.S., *CAD and CAE Analysis for Siphon Jet Toilet*, Physics Procedia, **19**(1), pp. 472-476, 2011.

[17] Yang, Z. & Shih, T.H., *New Time Scale Based K-epsilon Model for Near-wall Turbulence*, AIAA Journal, **31**(7), pp. 1191-1198, 1993.

[18] ANSYS FLUENT Theory Guide 16.0, ANSYS Inc., Canonsburg, PA, 2014.

[19] Zhou J.J., Xu G.Q. & Zhang H.J., *FLUENT Engineering Technology and Case Analysis (Volume II)*, China Water & Power Press, 2013.

[20] Ou, Y.J., Liu, Z.J., Liu, X. & Teng, G.H., *The Design and Analyse of Back Wash Toilet Passageways System*, China Ceramics, **47**(5), pp. 61-64, 2011. (Text in Chinese and Abstract in English)